Consumption awareness for energy savings: NIALM algorithm efficiency evaluation

G. M. Tina and V. A. Amenta
DIEEI University of Catania - Italy
giuseppe.tina@dieei.unict.it , valeria.amenta@dieei.unict.it

Abstract- **The worldwide adoption of smart meters that measure and communicate residential electricity consumption gives rise to the development of new energy efficiency services. Among these services, it is worth mentioning the ones related to energy saving. In this context it would be essential to know the energy daily profiles of the appliances of a public utility customer. These information can be obtained by means of Non Intrusive Appliance Load Monitoring (NIALM) algorithms. The efficiency of such algorithm are related non only to the number and type of appliances, but also to the quality of the data provide by the power meters. In this paper, we study how the use of disaggregation algorithms in conjunction with smart meters is cost-effective and scalable solution for energy efficiency systems. New efficiency definitions and load indices are also introduced to evaluate the performance of disaggregation algorithms.**

Keywords— Enrgy saving; load signature;disaggregation

I. INTRODUCTION

Shortage of traditional fossil fuels and increasing of greenhouse gases (GHGs) are the main energetic problems that have to be overcome all over the world as soon as possible to avoid dramatic environmental and economic impacts. In this context energy savings, that includes also energy efficiency (it implies simply using less energy to attain the same or greater level of performance output from various mechanical and electrical equipment and systems) contribute to security of energy supply, GHG emissions reductions, the fast and cheap achievement of a sustainable energy supply, and last but not least, significant job creation [1]. Specifically the EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020. The Commission has proposed several measures to increase efficiency at all stages of the energy chain: generation, transformation, distribution and final consumption. The measures focus on the public transport and building sectors, where the potential for savings is greatest. Other measures include the introduction of smart meters (which encourage consumers to manage their energy use better), and clearer product labeling [2].

Specifically significant low-cost energy reductions can be made in the residential and commercial sectors, but the savings have not been achievable to date. As billions of dollars are being spent to install smart meters yet the energy saving and financial benefit of this infrastructure will not reach its full potential without careful consideration of the human element [3].

In fact a good knowledge of where the energy is going is fundamental for the customers to decide how it is possible to reduce energy waste and maximize energy bill savings. There are different approaches for implementing energy efficiency programs, and basically two types of actions that can be taken: by changing the behavior and habits of the customers in what concerns the use of home appliances or by making investments in energy-efficient technologies. Many times, in order to achieve a significant improvement in energy savings, these two actions must be implemented simultaneously.

Currently a large effort is being done with the intention to educate people about how much energy each electrical appliance uses in their houses, since this knowledge is the fundamental basis of energy efficiency programs that can be managed by the household owners. There is a solution that allow at the same time to save energy and to use smart meters it is called energy disaggregation, it refers to a set of statistical approaches for extracting end-use and or «appliance level» data from aggregate, or whole-building, energy signal.

This paper presents a proposed overall ICT architecture for energy consumption awareness, among the various functions performed by it, a functional non-intrusive appliance load monitoring (NIALM) algorithm is analyzed, it can be used for electric power measurements that can be applied in energy efficiency programs, in order to provide a better knowledge of the energy consumption of the appliances in a home. Specifically indices of performances are introduced, and the reasons for low level of disaggregation are detailed analyzed. Finally some experimental results obtained in the power system laboratory of University of Catania-Italy are presented.

II. SYSTEM SETUP

A proposed overall ICT architecture for energy consumption awareness is shown in Fig.1: data about energy consumption collected in users' homes are sent to a service provider site that, after disaggregating and processing them, allows an user friendly representation of energy consumption providing several direct feedback to the user about his habits and distribution of consumption among his appliances [5].

In the local Monitoring System (LMS), at the common coupling point with the public distribution system, a power meter (PM) is installed to monitor locally electrical loads. After a properly data processing, they are transmitted via the web to a central server (SMC) where an higher level processing is performed. Both data collected locally and those drawn from the central server will then be made available to the user through an appropriate platforms.

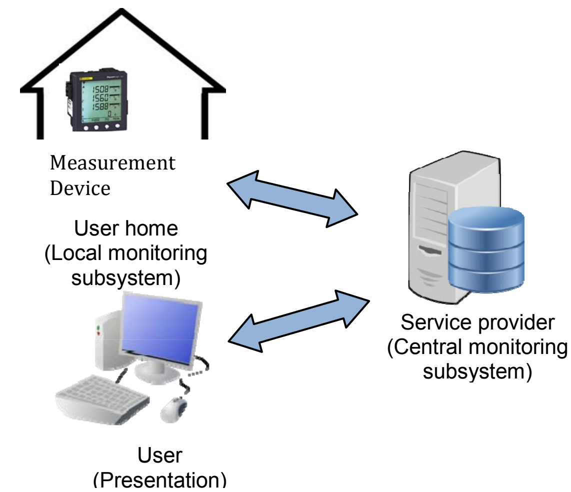

Fig.1. Architecture of the domestic load monitoring system.

The SMC using this information, through an appropriate mathematical algorithms, named NIALM, by means of individual appliance power consumption information is disaggregated from single-point measurements, provides a feedback in such a way to make energy more visible and more amenable to understanding and control. The first step for the evaluation of the efficiency of NIALM algorithms has been the experimental analysis of the measurements of two commercial power meter, named PM1 and PM2.

PM1 measures current and voltage and reports in real time the rms values for all three phases and neutral. In addition, PM1 calculates power factor, real power, reactive power, and others variables. It is also guaranteed a variation on the measurements of 0.5%. The updated frequency of the data is 1/second. The input current to the device is included in a range of values from 0 to 6 amperes, to ensure the protection of the device is appropriate to use a TA (current transformer). The data are transferred via the RS485 port and, a Modbus RTU protocol can be used. PM2 provides the same data as PM1. The measuring range of the current varies from a minimum of 0.02 to a maximum of 6 amps, and also in this case TA is necessary.

Both devices display the following electrical parameters: voltage (V), current (I), active power (P), reactive power (Q), apparent power (S), power factor (PF), voltage and current THD. PM2 can also display the harmonic content relative to each harmonic up to 22°.

The data captured by the two PMs can be classified in two types,: direct (V, I, PF) and indirect, that is processed internally by a micro-processor, (P, Q, S, THD).

The data provided by the power meter represent the inputs of the disaggregation algorithm. As in any measurement system, measurement errors have to be taken into account. These errors can impact greatly the efficiency of NIALM algorithm. So the measurements of the PMs have been compared.

The difference between the measured electrical indirect quantities and the analytical ones, by (1), that are obtained from the direct measurements are analyzed. Table I show the values of the direct and indirect quantities and the last ones have been evaluated also analytically. TABLE II show the errors calculated by (4), where the variable X can be P, Q and S.

$$P^* = V * I * PF \quad Q^* = V * I * \sqrt{1 - PF^2} \quad S^* = V * I \tag{1}$$

$$X_{error}\% = \frac{X^* - X}{X} * 100 \tag{2}$$

TABLE I. DIRECT AND INDIRECT QUANTITIES, FIGURES IN BRACKETS ARE CALCULATED

App.	PM	V (V)	I (A)	P (W)	PF	Q (VAR)	S (VA)
Lamp	1	228.7	0.35	33 (32.02)	0.4	75 (73.36)	82 (80.05)
	2	229	0.35	33.7 (33.66)	0.42	74 (72.74)	81 (80.15)
Computer	1	229	0.134	14 (12.58)	0.41	**65507** (27.98)	33 (30.69)
	2	229	0.29	32 (29.89)	0.45	59 (59.31)	69 (66.41)
Refrig.	1	227.4	0.5	103 (102.71)	0.90	49 (48.78)	114 (113.7)
	2	230	0.35	66 (64.4)	0.8	47 (48.3)	81 (80.5)
Radio	1	232.3	0.025	4 (3.71)	0.64	4 (4.5)	6 (5.81)
	2	230	0.023	3.81 (3.7)	0.7	4.12 (3.77)	5.46 (5.29)
Coffee Machine	1	228.2	5.91	1351 (1348.6)	1	0 (0)	1351 (1348)
	2	231	6	1350 (1025)	0.74	750 (932)	1360 (1386)
Microwave	1	224	4.3	1000 (935.5)	0.99	304 (135.8)	1000 (963.2)
	2	223	4.25	1000 (938)	0.99	270 (133)	1000 (947)

TABLE II. CALCULATED ERRORS

Appliance	PM	P_{error}%	Q_{error}%	S_{error}%
Lamp.	1	-2	2	-2
	2	0	1	-1
Computer	1	-10	-99	-7
	2	-6	0	-3
Refrigerator	1	0	0	0
	2	-2	2	0
Radio	1	-7	11	-3
	2	-2	-8	-3
Coffee Machine	1	0	-	0
	2	-24	24	1
Microwave	1	-4	-55	358
	2	-6	-50	360

Specifically, we have noticed that, in case of appliances characterized by an high harmonic content, PM1 is not able to provide reliable measurements (it displays just a default value), whereas PM2 provides correct values. Further PM2 has an error threshold lower than the PM1. In fact, PM2 uses a microcontroller of the last generation, this allows PM2 to be more reliable for electrical measurements even under the most critical conditions, such as voltages and currents with high harmonic content and variable frequency (e.g. PC computer).

Another important aspect is data transmission. PM1 and PM2 have a built-in isolated Half duplex RS-485 serial interface. The communication port setting is obtained through dedicated setup parameters. To connect to the web EGX100 is used; it is an intelligent Ethernet gateway, that is used to allow a remote full control and configuration of the PMs. PM1 allows us to be sampled at a frequency of 1 second, instead PM2 is slower as it provides a sample every 9 seconds. Using PM2 there is the risk to lose some information. During those 9 seconds some devices can switch on/off. This event can cause a lower efficiency in NIALM algorithm.

III. New Method for Load Identification

It is noticed that the procedures of NIALM are divided into two, that is to say, those analyzing the steady-state and those that focus on the transient detection [4][6]. Each electrical appliance has many rated characteristics. But in our case, two main features are considered: active and reactive power.

A simple NIALM algorithm for disaggregating of the overall load into individual appliances, has been developed. The algorithm is able to detect the consumers based on changes of active and reactive power consumption of two states (on-off) and multi-state appliances. This algorithm has been tested experimentally at the Power system Laboratory of University of Catania, where the load signature (LS) of certain appliances that might be found in a domestic environment have been performed. Fig.2 shows the experimental set-up. Different appliances have been monitored, such as a light bulb, a laptop, a refrigerator, a radio a coffee machine and a microwave. The appliances are modeled as on/off appliance that consume constant power at a single steady state. In reality, coffee machine loads depend on the water volume, the refrigerator have a second power state corresponding to defrosting.

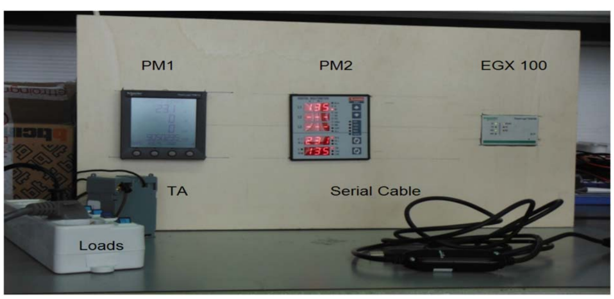

Fig.2 Experimental setup for data acquisition.

To evaluate quantitatively the performances of the proposed disaggregation algorithm, two different efficiencies have been defined. Further to understand deeply, the different causes of inefficiency of NIALM algorithm it has been decided to generate randomly load profiles (more details about this program are reported in the numerical analysis paragraph). So in the following these profiles are cited specifically as generated (lowercase 'g'), when the profiles come from random generation, whereas they are called disaggregated (lowercase 'd'), if they come from NIALM algorithm.

The first efficiency is based on the different, sample by sample of the generated and disaggregated power [5] [6]. In (3) only the active power efficiency is shown, but the reactive power efficiency has a similar definition.

$$\eta_p = \frac{\sum_{i=1}^{n_s} \left| P_{gd}(i) - P_{gg}(i) \right|}{\sum_{i=1}^{n_s} P_{gg}(i)} \tag{3}$$

Where:

i is the ith sample;

n_s is the number of samples;

P_{gd} is global disaggregated load profile;

P_{gg} is global generated load profile.

Due to compensation phenomena it can be happen that η_p can be very high (e.g 80% ÷ 90 %), but the profiles of the single appliance can be wrong. This is the reason why another efficiency has been introduced, that is η_s. It is reported in (4).

$$\eta_s = \frac{\sum_{j=1}^{n_a} \left\{ \left\{ \frac{1}{n_s} \sum_{i=1}^{n_s} \left[xor\left(SSA_{g,j}(i), SSA_{d,j}(i) \right) \right] \right\} * P_j \right\}}{\sum_{j=1}^{n_a} P_j} \tag{4}$$

Where:

j is the j-th appliance;

n_a is the number of appliances;

P_j is the rated power of jth appliance

$SSA_{g,j}(i)$ and $SSA_{d,j}(i)$ are logical values, that indicate the states of the appliance j at time i.

The logical operation xor, allows to have a value equal to one when $SSA_{g,j}(i)$ and $SSA_{d,j}(i)$ assume the same value (that can be either 0 or 1).

There are many factors that significantly affect the efficiency of the disaggregation algorithm, such as: measurement accuracy of power meters (normally ± 1% f.s. and + - 0.25 f.s.), electrical characteristics of the customer's appliances, and, finally it is related to actions that can fulfill the users.

As far as measurement accuracy is concerned, the Italian technical standard UNI-CEI ENV 13005, recognizes that "the result of a measurement is only an approximation or estimate of the value of the measurand and is therefore complete only when it is accompanied by a statement of the uncertainty of that estimate".

Related to the appliances electrical characteristics there are two important aspects that impact greatly the effectiveness of disaggregation: the first one is connected with the nominal power of appliances. In fact when in a domestic dwelling, there are appliances whose rated powers are too small or close each other, considering a given power threshold (e.g. 4 W), the efficiency tends to decrease. The second one is linked with the simultaneous switching on and/or off of two or more appliances.

In this context two factors that characterize a given group of appliances have been defined, that is KG_P and Dg_P.

$$KG_P = \frac{P_{\min}}{Lim\_DeltaP} \tag{5}$$

Where:

- P_{min} is the smallest value among the rated power of appliances belonging to a given group;

- Lim_DeltaP is a parameter, i.e. 4W, it is a threshold for the detection of the switching events.

$$Dg_P = \min\left\{\left|P_i - P_j\right|\right\} \quad where\, i, j \in \left[1, 2, ..., n_a\right] \tag{6}$$

Dg_P is the smallest value among the values obtained from the differences between the rated power of i-th and j-th appliance.

Finally it has been introduced another parameter, named global number of simultaneous switching – GNSS. Given a certain periods of time, for example a day, it is equal to number of sample characterized by simultaneous switching, n_{ss}, by the number of the involved appliances n_{ca}.

$$GNSS = \sum_{i=1}^{n_{ss}} n_{ca}(i) \tag{7}$$

IV. NUMERICAL ANALYSIS

The robustness of the disaggregation algorithm has been tested both numerically and experimentally. Specifically, in this section, the function, that randomly generates different and controlled load profiles is described. The main parameters that need to be set to generate a load demand profile are: the number of the appliances (n_a) and the number of samples (n_s), as well as deltaT, which is the minimum number of samples between a switch on and a switch off of an appliance. In this numerical analysis these parameters assume the following values: $n_a = 10$, $n_s = 500$ and deltaT = 2.

For sake of simplicity, in this numerical analysis, only ON-OFF appliances are chosen, whereas in the proposed NIALM algorithm also multi-state loads are considered.

Each appliance is characterized by its rated active power and power factor, that are randomly generated within a fixed range, In Table I, there are the list of the characteristics of two groups of 10 appliances, the range of power factor is equal for both, e.g. 0.2 ÷ 1.0, whereas the range of rated power for the first group is 10 W ÷ 100 W, whereas in the second group is 10 W ÷ 1000 W. Finally the load factors, defined in (5) and (6), are calculated considering the following parameters: Lim_deltaP=4 W and Lim_deltaQ=20 VAr. It is worth to noting that in the group A there are two appliances (e.g. 2 and 9, written in bold in Table I) whose rated active and reactive power differ by less than the respective tolerance (Lim_deltaP=4 W and Lim_deltaQ=20 VAr).

TABLE III. RATING OF APPLIANCES AND GLOBAL INDICES

	A: 10 W < P < 100 W			B: 10 W < P < 1000 W		
App.	**P(W)**	**Q(VAr)**	**cos(φ)**	**P(W)**	**Q(VAr)**	**cos(φ)**
1	86	21.6	0.97	804	201.5	0.97
2	**64**	**99.8**	0.54	228	304	0.60
3	***17***	25.8	0.55	318	230.2	0.81
4	25	15.5	0.85	468	213.2	0.91
5	29	32.1	0.67	***104***	30.3	0.96
6	86	114.7	0.60	295	292.6	0.71
7	91	153.5	0.51	746	782.6	0.69
8	50	46.8	0.73	599	174.7	0.96
9	**62**	**87.08**	0.58	327	176.5	0.88
10	77	30.4	0.93	894	181.5	0.98
KG	4.25	0.77	-	26	1.52	-
Dg	0	1.70	-	9	1.78	-

Fig. 3 shows an example of a generated global load profiles, active and reactive power, where: n_a is equal to 10, the number of samples, n_s, is 500. A numerical calculation of KG and Dg has been performed referring to the load profiles shown in Fig. 3, and the results are reported in TABLE III. The value reported in red is P_{min} in (5).

Considering the case (A) (see TABLE III and Fig. 3-A), the graphical results of the disaggregation algorithm, described in [7], are reported in Fig 4, where the global profile generated, named P_{gg}, is shown in red and the global profile coming from the application of the disaggregating algorithm, named P_{gd}, is shown in blue. The disaggregation efficiencies defined in (3) and (4) assume the following values: η_p = 75.08 % and η_s= 71.6 %. Such values are justified by the presence of two appliances (2 and 9).

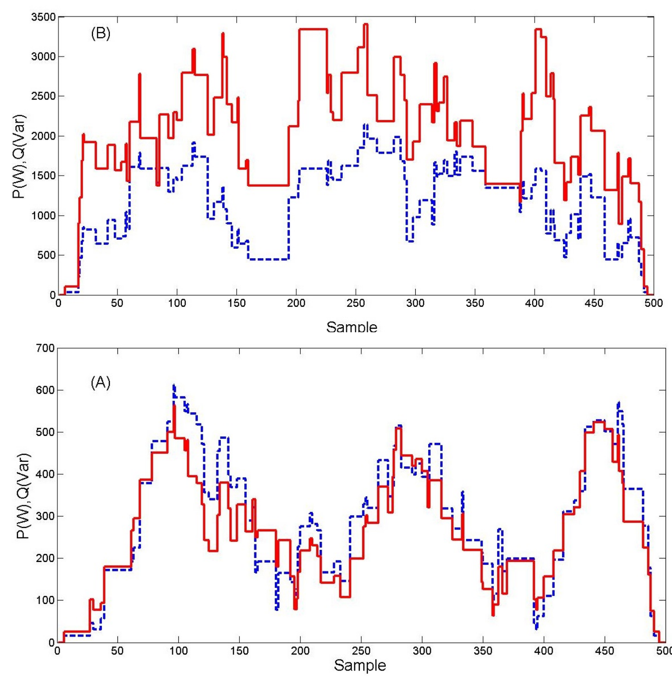

Fig. 3. Global generated load profiles: active power (solid red line) reactive power (dashed blue line): A) P=10÷100 W, B) P=10÷1000 W.

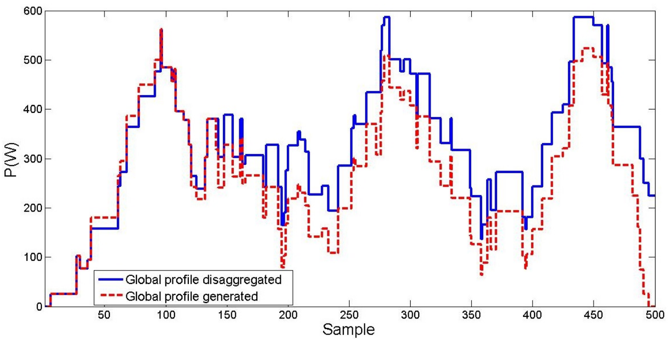

Fig 4. Global load profiles Pg: Pgg – generated (dashed red line) and Pgd (solid blue line).

Fig. **5** depicts an example of comparison between the generated (SSA_g) and disaggregated (SSA_d) status profiles of two appliances (2 and 9); since the appliances are of ON/OFF type, the status can be 0 (OFF) or 1 (ON).

Considering the two cases A and B in Table III, Fig. 6 shows the cumulative relative error derived from the progressive difference of P_{gg} and P_{gd}. The curves highlight that an initial disaggregation error progresses very rapidly.

Often changes in the derivative of these curves happen, they can be explained by means of compensation phenomena due to the presence, for instance, of two appliances that have P and Q ratings very close.

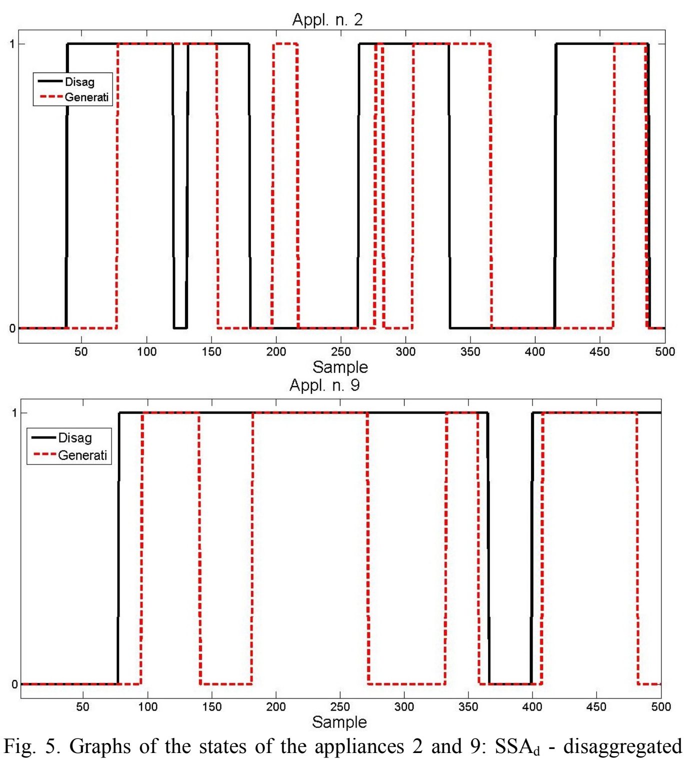

Fig. 5. Graphs of the states of the appliances 2 and 9: SSA_d - disaggregated (solid red line) and, SSA_g - generated (dashed black line).

To evaluate how the disaggregation algorithm works with different set of appliances, represented by the two indices D_{gP} and KG_P, twenty sets of appliances have been generated and the global profiles disaggregated. Fig. **7** a) and b) the η_p and η_s disaggregation efficiencies varying with respectively D_{gP} and KG_P considering 20 groups of appliances, randomly generated, that range among 10 W and 1000 W.

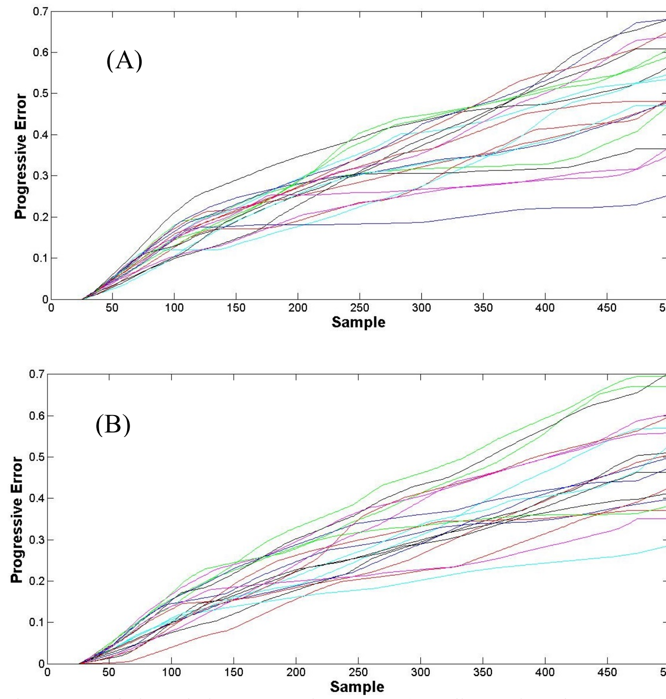

Fig. 6. Cumulative relative progressive error: A) appliances into the range 10÷100 W and B) appliances into the range 10÷1000W.

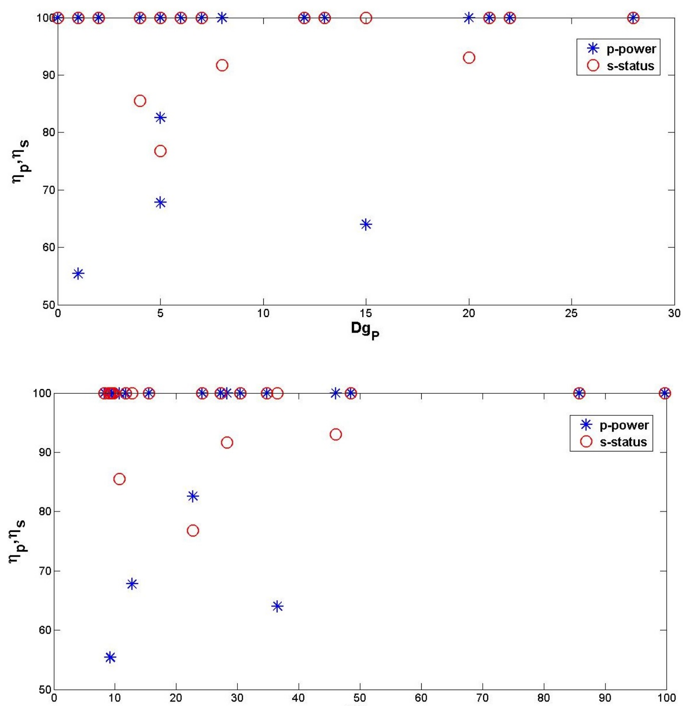

Fig. 7. η_p and η_s disaggregation efficiencies for appliances into the range 10÷1000 W: a) varying with Dg_P and b) varying with KG_P.

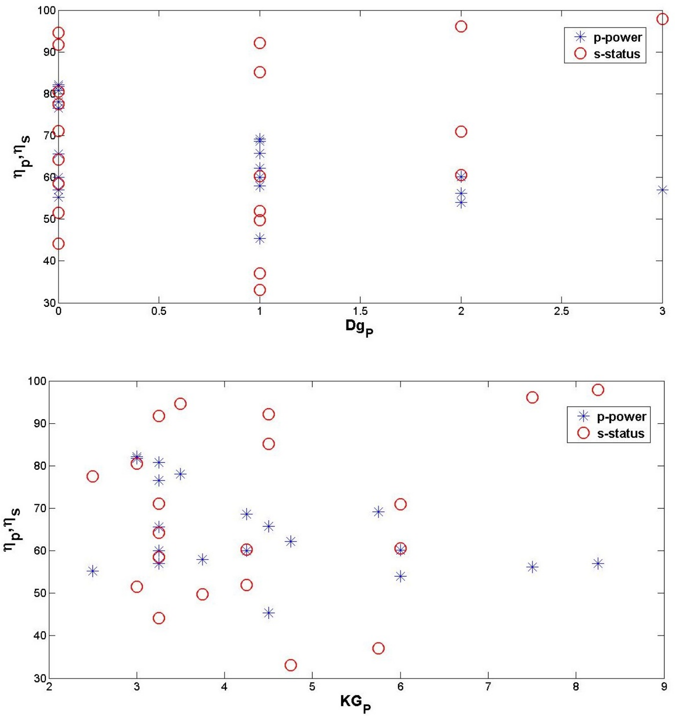

Fig. 8. η_p and η_s disaggregation efficiencies for appliances into the range 10÷100 W: a) varying with Dg_P and b) varying KG_P.

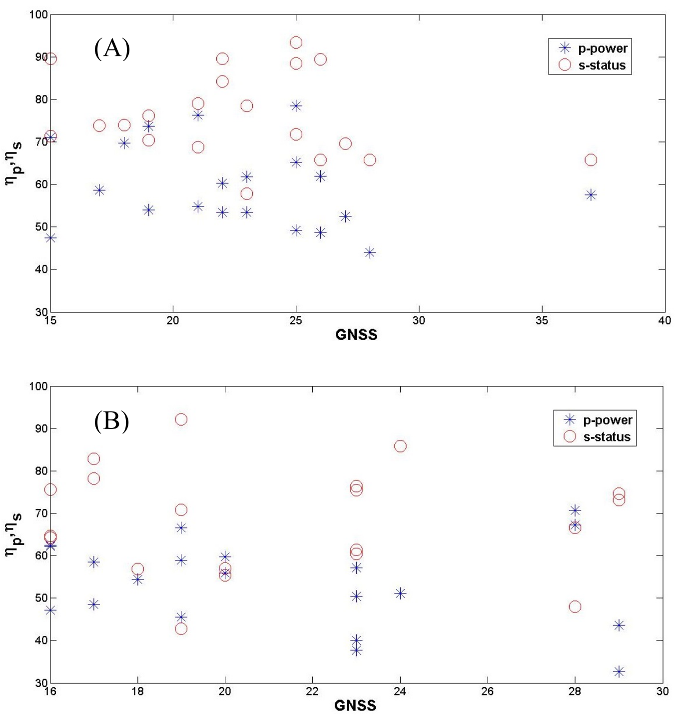

Fig. 9. disaggregation efficiencies varying with GNSS for appliances into A) the range 10÷100 W and into B) the range 10÷1000 W,.

We note that when the generated values of the rated power are below the threshold are varied, so it is clear that the values, obtained by disaggregation, are less than 90%. Then, we have increasing the range of nominal power, so the cases in which the differences between the powers are below the threshold decrease significantly, obtaining a percentage of disaggregation at 100%. Whereas Fig. 8 a) and b) shows the results about 20 groups of appliances, randomly generated, that range among 10 W and 100 W. Considering the case A) and B) of the TABLE III, Fig. 9 shows how the simultaneous switching influences both status and power efficiencies.

V. CONCLUSION

The disaggregation efficiency of the proposed NIALM algorithm is analyzed. The impact of different causes of inefficiency is evaluated numerically considering random generated load profiles, based on a certain set of appliances with given characteristics. From the analysis of the proposed graphs, it is evident that an algorithm, based just on the variation of active and reactive power, is not able to cope adequately with such problems: 1) the presence in the set of appliances of both loads whose rated powers differ less than a given value and small loads; 2) multiple switching.

When, due to the aforementioned problems, there is a wrong choice of the switching appliance, the error increases rapidly except that compensation events happen.

This is the reason why in the proposed ICT architecture for energy consumption awareness a software module that manages the customer feedback has been introduced. Subsequently, during the normal system activity, the user can be engaged in two different kind of interaction: checking of status and verifying signature.

ACKNOWLEDGMENT

This work is developed under the SEEE project funded by the POR FESR Sicilia 2007-2013 program.

REFERENCES

[1] Ecofys, Fraunhofer ISI (2010): Energy Savings 2020. How to triple the impact of energy saving policies in Europe. Final report. On behalf of the European Climate Foundation & Regulatory Assistance Project. September 2010.

[2] http://ec.europa.eu/energy/efficiency/index_en.htm

[3] K. C. Armel, A. Gupta, G. Shrimali, A. Albert, "Is disaggregation the holy of energy efficiency ? The case of electricity," Energy Policy 52 (2013) 213-214.

[4] C. Laughman, K. Lee, R. Cox, S. Shaw, S. Leeb, L. Norford and P. Armstrong, "Power Signature Analys*is*", IEEE Power and Energy Magazine, vol. 1, No. 2, 2003, pp. 56-63.

[5] G.M.Tina,S.Gagliano,V.A.Amenta, "Web interactive non intrusive load disaggregation system for energy consumption awareness", National Conference AEIT, Mondello , 3-5 October 2013.

[6] J. Liang, S.K.K. Ng, G. Kendall, J.W.M. Cheng, "Load signature study-part I: basic concept, structure, and methodology," IEEE Trans. Power Deliv. 25 (2) , (2010), pp. 551-559

[7] G.M.Tina, S.Gagliano,V.A. Amenta, "Non-Intrusive Load Monitoring Techniques for Energy Emancipation of Domestic Users," CISBAT International Conference Lausanne 4-6 September 2013