IEEE Transactions on Power Delivery, Vol. 6, No. 4, October 1991

USING APPLIANCE SIGNATURES FOR MONITORING RESIDENTIAL LOADS AT METER PANEL LEVEL

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ABSTRACT

As an initial approach, in order to identify electrical household appliances strictly by analyzing variations in current-voltage signals at meter panel level may seem to be utopian or, to say the least, an ambitious undertaking.

However, on observation of the currents consumed by these appliances it is surprising to see that each one of them is recognizable and perfectly identifiable by a certain number of parameters. Nevertheless, difficulties flow from the fact that an appliance is generally switched on while other appliances are already in use. The main issue is then to isolate the characteristic parameters of the appliance from the aggregate signal. One is also aware that the success of the identification does not only depend on the efficiency of the monitoring device, but also on a set of circumstances relating to the composition of the range of appliances installed on the measurement site, and the random sequencing of their operation.

This paper presents a study whose aim is to show the feasibility of this device. In particular, it presents the test findings secured on site using a test prototype.

A- INTRODUCTION

The growing share of the residential sector in electrical energy consumption (> 30%), makes for the growing need to secure informations on the apportionment of consumption by type of appliance. However, although it is relatively easy to identify the loads and applications in the industrial sector, their identification in residential premises remains much more difficult by reason of the number of customers and the diversity of appliances used. Two methods are presently followed to secure this informations:
1) sample enquiries;
2) individual load monitoring devices, in particular:
- individual meter-recorder,
- individual current sensor and central concentrator-recorder devices.

However, these methods are not frequently used by reason of their prohibitive cost and the disturbance they cause. They are earmarked to the study of some energy-intensive appliances.

91 WM 016-6 PWRD A paper recommended and approved by the IEEE Power System Instrumentation & Measurements Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1991 Winter Meeting, New York, New York, February 3, 1991. Manuscript submitted April 9, 1990; made available for printing November 30, 1990.

At an EPRI symposium, E.C. KERN [1,2] suggested the development of a measurement device which could monitor loads by identifying a signature at metering panel level. This idea is quite appealing. Its implementation should yield a relatively low-cost and not over-cumbersome monitoring device. The present paper outlines the work conducted by EDF in this regard. It shows in particular the test findings secured and describes the development principle of this device.

B- GENERAL CONSIDERATIONS

At metering panel level, an observer who switches an electrical appliance on or off witnesses variations in current-voltage signals. The identification of the appliance responsible for these variations necessitates the definition of a certain number of identification parameters and a measurement procedure.

Depending on circumstances, these parameters are sufficient or insufficient for the identification of the appliance in question. In the latter case, information on use is required regarding the operating conditions of the appliance.

The monitoring process should therefore be in three stages:
- learning of load characteristics;
- acquisition of events;
- identification of loads.

These three stages are practically independent. They can be performed at different times within a same apparatus or by different apparatuses.

Consequently, the device can be designed in two ways:
1) an "events meter" is developed; its role is strictly to memorize events in the form of identification parameters. A central computation unit then processes meter readings in a second stage.
2) a "compact apparatus" is developed; it can be used to execute the three operations indicated above and display an information of the type "appliance x was switched on at time t".

The events meter in fact reproduces a load curve recording. In addition to monitoring appliances, the meter reconstitutes classical averaged load curves or allows short consumption peaks to be examined.
Off-line processing of readings does away with time constraints and thereby allows an efficient identification algorithm to be developed. An ideal representation of the system would be as follows:
- a park of meters installed at customers' premises;
- a central unit receiving the data acquired by the meters;
- an identification algorithm based on an expert system which is progressively developed to form a database listing the identification parameters of the various electrical household appliances and a database of facts associating a certain identification method with each type of appliance, exploiting its most striking characteristics.

The "compact apparatus" version corresponds to a more selective view of objectives. If attention is paid only to certain types of loads, the construction of a compact apparatus is simpler. Its main feature is that it is used to select interesting events immediately after the measurements and to store a more limited volume of information than in the events meter version.

C- THE MEASURABLE MAGNITUDES

Three main magnitudes can be acquired from the metering panel with a digital measurement device:

- the effective current value $I = \sqrt{1/T \int i^2 \, dt}$
- the effective voltage value $U = \sqrt{1/T \int u^2 \, dt}$
- active power : $P = \sqrt{1/T \int ui \, dt}$

Apparent power $S = U \, I$ can be deduced from these magnitudes, and reactive power calculated from :

$$Q = \sqrt{S^2 - P^2}$$

Given that the voltage module can fluctuate over time, powers must be reduced to a fixed benchmark voltage U_{ref} which is taken equal to the rated voltage of the network. Whence:

$$P_{ref} = P/U^2 * U^2_{ref} \quad \text{and} \quad Q_{ref} = Q/U^2 * U^2_{ref}$$

In addition to its power, an electrical appliance signature can comprise data on:
- the duration and shape of the current transient when switched on,
- the current harmonics produced by the appliance.

These last pieces of information are nevertheless not necessarily significant for all types of appliances.

D- MAIN TYPES OF HOUSEHOLD APPLIANCES

Electrical household appliances can be classified by type using the former magnitudes. This classification does not take the use of the appliance into account, but the image (or the signature) it returns to the measurement point. The first stage of the monitoring process is therefore the identification of the type of appliance.

On-site observations afford the general classification given below:

1) resistive appliances :
They form the largest category, encompassing:
- heating appliances such as panel heaters, cookers, ovens, etc ,
- heating elements of the washing machine, dishwasher or other complex appliances,
- incandescent lighting.

These appliances are characterized by:
- zero reactive power,
- no transient when switching on, or a very short transient (lower than the 50 Hz period),
- absence of harmonic components of the current.

Active power is therefore the principal measured value used for their identification.

2) pump-operated appliances:
These are electric motors driving a pump. Several electrical household appliances enter this category, in particular: refrigerator, deep-freeze, dishwasher and washing-machine drain pumps etc. These appliances are generally characterized by:
- substantial reactive power,
- long and characteristic transient when switched on,
- odd-numbered harmonic current.

3) motor-driven appliances:
This category encompasses the other appliances bearing an electric motor such as a washing-machine, fans or various types of mixers. These appliances differ from pump-operated appliances by their generally less substantial switching on transients.

4) electronically-fed appliances:
This category comprises low consumption appliances such as televisions, video-recorders, personal computers or High Fidelity equipment. They are characterized by:
- short but very high amplitude switching on transient;
- a current spectrum rich in harmonic components.

5) electronic power control appliances :
This category includes various appliances which are increasingly encountered everyday, such as halogen lights, some convectors, some vacuum cleaners or some cookers. Their characteristics generally vary with the power level at which they operate. Their identification is therefore quite difficult and have therefore not been considered at this stage of the study.

6) fluorescent lighting :
This type of lighting is characterized by:
- a long two-step switching on transient,
- very high generation of the third harmonic of the current,
- substantial current-voltage phase shift.

To illustrate this classification, figures 1 to 4 show some typical examples of wave shapes and spectra of some everyday electrical household appliances.

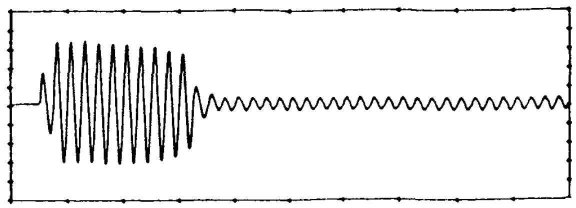

Figure 1 : switching on refrigerator current

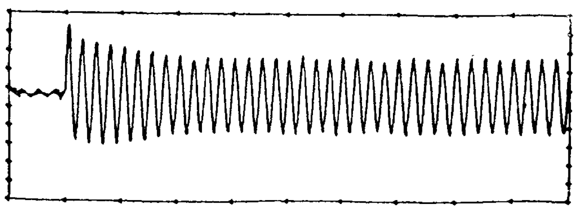

Figure 2 : switching on washing machine motor current

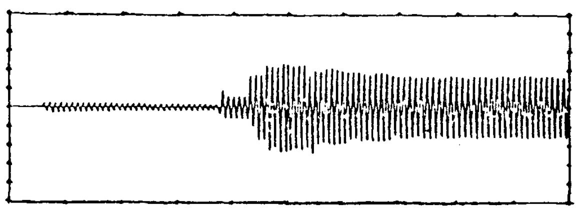

Figure 3 : switching on fluorescent light

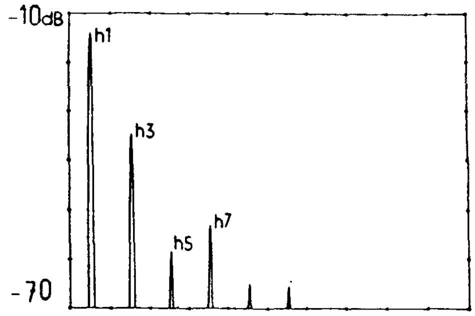

Figure 4 : Spectrum of a fluorescent light

Figure 5 shows the dispersion of characteristic values of the most popular appliances in an active power-reactive power plane. The following can be observed in particular:
- the large number of appliances located about the horizontal axis (resistive appliances);
- the high density of appliances in the zone below 300 Watts;
- the quasi-absence of capacitive appliances.

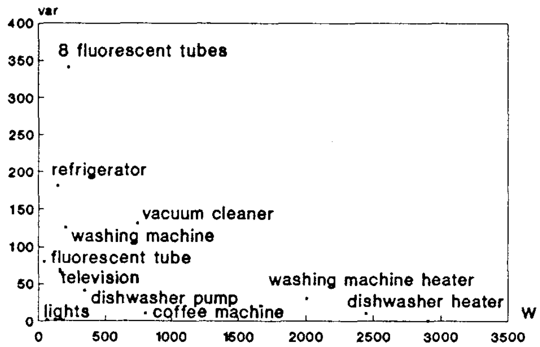

Figure 5 : Relative positions of different appliances in the complex P, Q plane.

D- MEASUREMENT PROCEDURE

Switching an appliance on or off is generally done with other appliances already in operation. Identification is therefore not linked to the current value but to its variation. The role of the measurement procedure is to read the signature of the appliance, isolating the parameters with which it can be identified at each signal discontinuity.

Three main problems are posed at this level:

1) resolution of the measurement
To identify an appliance, its power must be clearly higher than the minimum resolution of the measurement device. In addition, the power difference between site appliances must be higher than the same resolution so as not to mistake this appliance for another.
In practice, the values of u and i are derived from a numerical measurement. A minimum resolution of 12 bits seems to be necessary. Taking account of the fact that the power of an appliance is the outcome of two measurements, one before it has been switched on and one after, it can be shown that with 12 bits, the accuracy of measurement is approximately $\pm$ 0.15%, i.e. 15 Watts for a device calibrated at 10 KW maximum.
Greater resolution is required for measuring harmonics. The power of household appliances generating harmonics is generally low, and the harmonic current variations to be detected remain very low. The accuracy with which they are measured also depends considerably on the pre-existing rate of harmonics in the voltage.
It should nevertheless be remarked that a simple unqualified information of the type "the harmonic of order h has varied after an appliance has been switched on" is a useful piece of information. Associated with other information at hand, it allows an event to be attributed to a particular appliance rather than to another.

2) current fluctuation and drift:
In steady conditions, the current set up by a large number of electrical household appliances experiences two types of fluctuations:
a- fluctuations due to load variations, as in the case of a vacuum cleaner or the motor of a washing machine,
b- a drift linked to the increase in resistivity due to heating. This is the case of most heating appliances which only reach a stable regime after several minutes of operation. The power consumed by these appliances can vary by 5% to 10% depending on whether it is measured when the appliance is switched on or off. For example, the power of a 1000W convector is normally recorded at 1020W when switched on and 900W to 950W when switched off.
These phenomena are disturbing, since they can lead to major differences between actual and benchmark values.

3) detection of events:
The measurement device should detect events corresponding to a current variation and put them in parametric form by differentiating between conditions before and after the event. This kind of detection is difficult to perform with a purely analogic device because the issue is to detect level variations, not a rated level. Two types of numerical measurement procedures can be envisaged:

a- Asynchronous measurement:
This consists of measuring P and Q cyclically at regular intervals (a few seconds), which reduces to displaying a load curve.
However, experience shows that events can occur with time differences of the order of one second. This probability is the greater, the higher the number of appliances on the site or when a short-cycle appliance, such as a washing machine is in operation. In these conditions, several scenarios can make the interpretation of the measurement very difficult, in particular :
- if several events occur between two successive readings,
- if a measurement includes the moment at which the event occurs,
- if a measurement comprises a major transient.
To prevent this, the interval between measurements must be shorted, which leads finally to the continuous measurement method described bellow.

b- Continuous measurement
This consists of performing on-going measurement of the current signal by integrating it over a small number of periods (5 to 10 periods) and comparing each measurements with the former. If a variation is detected, it can then be analyzed and the identification parameters computed locally.
This method has several advantages:
- the detection of events can be accurate since it can involve complex numerical tests,
- a certain number of earlier measurements can be stored in memory, which allows the event to be identified locally (the signal before, during and after the event is available),

- it allows the transients to be analyzed .

This last method has been used for our experimental prototype.

E- INFORMATIONS ON USE

The last stage of the process is necessarily a comparison between measured parameters and a table of values acquired during the learning stage. In the light of the different problems highlighted in the previous sections, this comparison is not always easy. The measured parameters alone are often not sufficient to identify an appliance responsible for the event. A choice must then be made between several appliances. Information on use enters at this stage, thus facilitating a choice.

The nature of information can differ markedly, for instance:

1) switched on/off stage,

2) the cycle ;

There are two types:

a- constant duration pre-programmed, as for washing-machine and dishwasher;

b- variable duration, as for thermostatic switch appliances whose cycle varies with respect to external parameters. For instance, the cycle of a panel heater depends on outside temperature.

Although in the first case, the cycle can be viewed as a datum permitting forward measurement, in the second case the identification algorithm should be able to monitor the cycle and estimate its length.

3) association of events ;

In the case of loads formed by several appliances, preference can be given to the choice of an appliance from the time other appliances have definitely been detected. For instance, if the heating resistance of a washing-machine is monitored, preference can be given to the choice of its motor or its drain-pump for the duration of the washing cycle.

4) date of events ;

Knowledge of the use of the appliance promotes its choice with respect to times and dates. For instance, preference is given to the choice of the refrigerator for an event occurring at 3 a.m., and the coffee-maker for an event occurring between 7 and 8 a.m.

This information on use is a basic factor for identification, providing facilities to palliate the uncertainties of measurement. Its integration into the identification algorithm is nevertheless not always easy owing to the fact that it is not formulated by mathematical relations but by estimates based on logical reasonings. Its use indeed enters the framework of an "expert system" approach.

F- THE IDENTIFICATION ALGORITHM

The expression of an algorithm whose purpose is to identify a specific appliance is generally relatively easy. By contrast, expressing an algorithm which can identify any appliance is more complex. Several approaches are possible; two are analyzed here:

1) distribution into zones :

This method consists of defining specific zones to each appliance in the P, Q plane. The area of each zone is defined as a function of the degree of uncertainty attached to the measurement for the appliance considered. When the measurement yields a point located in a part of the plane where several zones override, reference is made to information on use or to the transient to be able to make a decision as to the choice of appliance.

If a harmonics analysis is available, the P, Q plane can be reproduced for several harmonics components and it can a priori be expected that the overriding of zones will not be the same in the different planes.

In practice, the efficiency of this method is limited. A large proportion of household loads is induced by resistive or not very inductive appliances. Uncertainty is portrayed by a straight line, not a zone, for these appliances. In general, they do not generate harmonic currents, and the P, Q planes of harmonics are not useful for their identification. In addition, the margins of uncertainty are not very well known from the outset for the different appliances. These margins are linked to the resolution of the measurements, as well as to current drift and fluctuation; their determination is quite cumbersome, necessitating a long period of prior observation.

2) iterative sorting :

It consists of searching, in a first stage, the events corresponding to benchmark values and meeting certain narrow margins of uncertainty. An incomplete image of the historical diagram of operation of the appliance is determined using events thus monitored. In a second stage, using supplementary parameters (transient, on/off cycle, etc.), an attempt is made to determine a complete historical diagram by attaching to this appliance events, among those which have not been identified, that best meet its type of use.

This last method was implemented on the test prototype.

G- THE TEST PROTOTYPE

The test device was developed using an AT-compatible portable micro-computer fitted with a 12-bit A/D conversion card. Its configuration is of the "events meter" type.

1) acquisition of events :

The device displays the measurement files in which the events are put in parametric form by four magnitudes:

- active power variation;
- reactive power variation;
- duration of transient;
- date.

Its principle is as follows :

- signals u and i are acquired with 5-period buffers sampled at 1.5 KHZ (i.e. 30 points per period for each signal);
- P and Q are continuously computed by integration of samples;
- a revolving memory keeps the last three measured values P0, P1 and P2;
- the difference P2 - P1 is continuously tested,
- if $P2 - P1 > \delta$, in which δ is the detection threshold, P0 is kept and time is given for the value of P to stabilize to check that the transient is completed (i.e. $P2 - P1 < \delta$);
- the event is then characterized by dP = P2 - P0 and dQ = Q2 - Q0;
- the duration of the transient is then assessed by analyzing crest current values or the effective values integrated over a half-cycle.

2) processing of measurements :

It comprises the following stages:

- acquisition of the benchmark values of the appliances to be sorted;
- definition of sorting conditions, in particular the margins of uncertainty;
- sorting.

The identification algorithm processes the whole measurement file as a block of data in which the elements are linked by certain relationships. It uses "missing events" search procedures to determine the logical operating cycles. Sorting is conducted in several stages; in the first stage, definite event are selected, whereas in the following stages, the historical diagram of each appliance is completed by applying, among the unidentified events, those which best meet its on/off cycle.

H- RESULT OF ON-SITE MEASUREMENTS

Figure 6 shows the historical diagrams of active and reactive powers recorded by the device in an occupied house over 24 hours. The operating cycles of some typical appliances monitored by the identification algorithm using events represented on this figure are given as an illustration in figures 7 to 9.

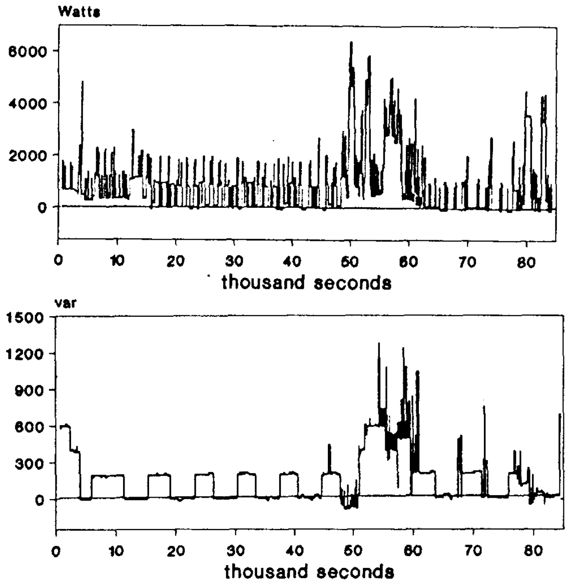

Figure 6 : Trend of consumption of household over 24 hours (t_0 = 5 pm). The refrigerator cycle appears clearly in the diagram of reactive power.

Figure 7 shows a 950W panel heater observed over 12 hours. It operates cyclically and the length of the cycle is variable. It reaches its maximum value in the afternoon and is at its minimum early in the morning.

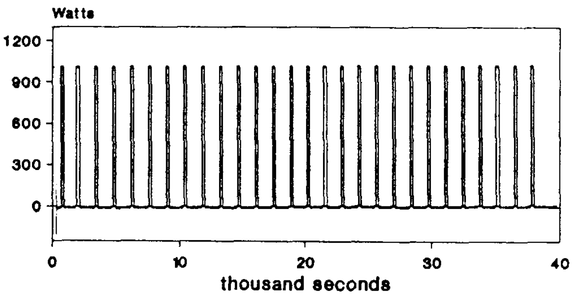

Figure 7: Operating cycle of a 950W heat panel sorted from figure 6

Figure 8 shows a more complex case, namely, that of two identical 800W panel heaters. In this case, although the determined on/off cycle is logical, it is far more difficult to check its accuracy and to monitor possible errors.

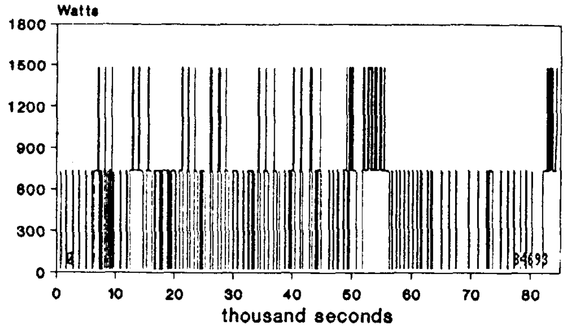

Figure 8 : Operating cycle of two identical 800W heat panels sorted from figure 6

Figure 9 shows the operating cycle of a washing machine. It is determined by monitoring its two components: the motor and the heating resistance.

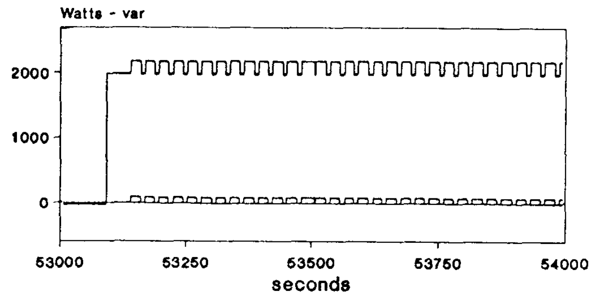

Figure 9 : Operating cycle of washing machine sorted from figure 6

The tests performed to date are not sufficient to be able to define a statistical success rate of identification. Monitoring of loads does not only depend on the performance of the measurement device and the sorting algorithm, but also on the random character of the combination of events. However, the measurements can point up trends and mainly reveal a certain number of problems. To this end, it is interesting to examine the results of the two stages of the process separately:

1) acquisition :
The detection system designed is satisfactory in allowing events to be effectively detected, even those of low amplitude (lower than 0.2% of the calibration threshold). Problems basically arise when the detection threshold is very low (lower than 50W). Current fluctuations and drift then sometimes lead to sudden triggering of the measurement.
It should also be observed that the measurement of the length of the transient is not always reliable. Events due to resistive appliances are sometimes read with a transient of a few periods. The belief is held that these phenomena can be attributed to contact arcs in the switches or the thermostats. In these cases, also non-zero reactive power has often been measured.

2) sorting :
In general, the identification algorithm has also shown good results. When the benchmark values and the sorting margins are well selected, it can identify more than 95% of the events due to appliances with simple operating cycles such as those presented in the above figures.
Identification problems are posed in the following cases:

- when the parameters characterizing the event do not match the measurement owing to an acquisition problem;
- when the appliance has several components whose operating conditions are combined in different manners;
- when the power of the appliance is variable.

However, in most of these cases, the development of a more powerful algorithm can solve these problems.

I- CONCLUSION

At the present stage of the study, the belief is held that a device which can monitor households loads can be designed.

The study presented in this paper shows that a local measurement of variations in active and reactive power is sufficient in most cases to identify an appliance. This measurement must be synchronized with the events. This necessitates a numerical measurement device which can monitor the signal and isolate the times when variations occur. In a second stage, a sorting algorithm identifies the appliance that has operated.

It must finally be observed that this selective acquisition method can be applied to other domains, in particular, fields in which a signal must be monitored and only some sequences used (e.g. measurement of disturbances) or even applications which require issuing a command following an analysis of events (control of a process by correlation of events, without using sensors). It is also quite probable that these devices may be put to use for applications such as the study of load curves in the tertiary sector and in industry, or for home automation projects.

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F. Sultanem was born in 1950. He obtained his Dipl. Eng. in 1973 from the university of Aleppo, Syria. In 1977 and 1981 he obtained the degrees of Dr. Eng. and Phys. Sc. Dr. from the University Pierre et Marie Curie in Paris.

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