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Non-intrusive appliance load monitoring system based on a modern kWh-meter

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ABSTRACT

Non-intrusive appliance load monitoring (NIALM) is a fairly new method to estimate load profiles of individual electric appliances in a small building, like a household, by monitoring the whole load at a single point with one recording device without sub-meters. Appliances have special electrical characteristics, the positive and negative active and reactive power changes during the time they are switched on or off. These changes are called events and are detected with a monitoring device called an event recorder.

Different NIALM-concepts developed in Europe and in the United States are generally discussed. The NIALM-concept developed in this study is based on a 3-phase, power quality monitoring kWh-meter and unique load identification algorithms. This modern kWh-meter with a serial data bus to a laptop personal computer is used as the event recorder. The NIALM-concept of this presentation shows for the first time how a kWh-meter can be used at the same time for billing, power quality and appliance end-use monitoring.

An essential part of the developed NIALM-system prototype is the software of load identification algorithms which runs in an off-line personal computer. These algorithms are able to identify, with a certain accuracy, both two-state and multi-state appliances. This prototype requires manual-setup in which the naming of appliances is performed.

The results of the prototype NIALMS were verified in a large, single family detached house and they were compared to the results of other prototypes in France and the United States, although this comparison is difficult because of different supply systems, appliance stock and number of tested sites.

Different applications of NIALM are discussed. Gathering of load research data, verification of DSM-programs, home automation, failure analysis of appliances and security surveillance of buildings are interesting areas of NIALM. Both utilities and customers can benefit from these applications. It is possible to develop an automatic-setup NIALMS for households but it needs a large data base of signatures of different appliances.

PREFACE

This report is a consequence of four years research and development work concerning non-intrusive appliance load monitoring. The idea to begin this work originated in 1993 when the national energy research program (LVIS-2000) for buildings was finished. During the program the use of electricity for different loads in certain buildings was monitored and it was found to be very difficult and expensive to install intrusive recorders.

The work has been supervised by professor *Tapani Jokinen*. I am grateful to him for his cooperation and support. I owe many thanks to research professor *Seppo Kärkkäinen* from VTT Energy for research management, enthusiasm and support while studying these new matters.

During the development of the prototype NIALMS many persons have participated in this work. Mr. *Martti Siirola* from VTT Automation wrote the source code for the event recording software and performed many recordings in the laboratory. Mr. *Pekka Koponen* from VTT Energy and Mr. *Seppo Vehviläinen* from Mittrix Oy were responsible for developing the power quality monitoring kWh-meter which was modified according to the needs of NIALM. Mr. *Juho Farin* from VTT Energy designed and developed the cluster analysis part of the load identification software. Mr. *Yrjö Rantanen* from VTT Energy offered his home as the field testing site for a number of years and there performed several separate recordings in order to verify NIALMS results. He also designed and constructed the unique, non-intrusive portable briefcase metering system. It was possible to perform the verification of results with the equipment borrowed from the Electricity Association in the United Kingdom thanks to Mr. *David Cooper*. Mr. *Juha-Pekka Rissanen* has collected, during his Master's thesis work, appliance data which will be very valuable during further development of the prototype. Mr. *Matti Simppala* from Imatran Voima Oy installed meters in commercial buildings and participated in follow-up results in these sites. I want to thank all these persons and also many others not mentioned individually who have participated in this work from VTT and at the monitoring sites.

For the financial support I want to thank VTT Energy, the Association of Finnish Electric Utilities, Technology Development Centre TEKES and Imatran Voima Foundation.

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Hannu Pihala

CONTENTS

SYMBOLS

AS-NIALMS	Automatic-Setup NIALMS
dP	the difference between after-event and before-event active power values = on or off transition active power of an appliance
dP_{tol}	maximum active power difference between successive samples during steady state period
dQ	the difference between after-event and before-event reactive power values = on or off transition reactive power of an appliance
dQ_{tol}	maximum reactive power difference between successive samples during steady state period
DSM	Demand Side Management
$E_{\mathrm{est}(i)}$	non-intrusively estimated electricity consumption of an appliance during day *i*
$E_{\mathrm{true}(i)}$	exact measurement of electricity consumption of an appliance during day *i*
EDEVE	**E**dF/**D**efu/**E**fi/**V**TT Energy/**E**lectricity Association
I	phase current, RMS value
I_h	harmonic current of order *h*
I_{1f}	fundamental frequency current
φ	phase angle
φ_{1f}	fundamental frequency phase angle
MS-NIALMS	Manual-Setup NIALMS
MXPQ	kWh-meter type from Mittrix
MXPQL	power quality monitoring kWh-meter type from Mittrix
NIALMS	Non-Intrusive Appliance Load Monitoring System
P	total active power
P_i	active power consumed by an appliance operating in a steady state *i*
Q_{F}	Fryze's reactive power
Q_{1f}	fundamental frequency reactive power
Q_i	active power consumed by an appliance operating in a steady state *i*
Q_{H}	non-fundamental reactive power
S	apparent power
$s_k(t)$	state of an appliance *k*
t	time (point)
U	phase voltage, RMS value
U_h	harmonic voltage of order *h*
U_{1f}	fundamental frequency voltage
W	energy consumed by an appliance during a certain period

1 INTRODUCTION

Increased interest in energy monitoring, load forecasting and improved control of electrical appliances has focused attention on the instrumentation required to obtain the desired data. In addition end-use load data can be used in the evaluation of demand-side management (DSM) programs. Utilities can design advanced tariffs based on load data and in building automation systems the state of appliances can be used for fault diagnostics and calculation of energy consumption etc. Therefore the need for a low cost and easy-to-install electrical end-use appliance load monitoring system for buildings is evident.

Traditionally sensors are installed on each of the individual components of the load. This work deals with an advanced method: Non-Intrusive Load Monitoring (NIALM) techniques, where monitoring of the whole load at short intervals is done at a single point. Also the term centralized load monitoring describes this technique where step changes in active and reactive power are detected and stored with time marks. The end-use consumption of individual loads is estimated using sophisticated pattern recognition algorithms. Traditional load monitoring systems require complex hardware and simple software, while the NIALM-system reverses that balance.

Excluded from the scope of this work are engineering and statistical models for separating loads, by annual energy use or load shape, in large numbers of buildings grouped by classes.

1.1 OVERVIEW OF NIALM HISTORY AND STATUS TODAY

NIALM-systems have a short history: the first ideas to develop a NIALM system were introduced 1982. The pioneer country was the United States. In 1989 France also begin to work on a design for a load monitor for NIALM. At the end of 1993, in Finland, VTT Energy considered the idea of developing a NIALM-system based on a modern three-phase kWh-meter. The following is a short summary representing the situation in different countries having developed their own load monitor.

1.1.1 The United States

First the concept of analyzing power flows to determine the set of appliances in a home and report on their on- and off-events occured to professor George W. Hart in 1982 at the Massachusetts Institute of Technology while collecting and analyzing load data as part of a residential photo-voltaic systems study (Hart 1992). He monitored electricity consumption of homes at 5 second intervals and was struck by the fact he could “read” the plots visually and tell what was happening in the monitored homes. So he begin to formalize the steps to write a computer program which made a similar analysis. This was the start to developing a fully new monitoring system for end-use appliances. Together with MIT Energy Laboratory Staff they realized that this kind of system could have significant value to utilities.

Since that time professor Hart has carried out the basic research and development with EPRI (Electric Power Research Institute) sponsorship. He designed and implemented the first two prototypes and specified the algorithms for the third prototype. The hardware prototype was a unit housed as a module separate from the meter, with signals being captured through a meter extender to the service entrance. The goal of this development work has been to introduce an Automatic-Setup NIALM for households, which sets itself up as it measures the load. Because of this ambitious goal it has taken more than 10 years to commercialize this system. After many field tests a company named Telog Instruments, Inc. is planned to begin marketing the system during 1998 (Technologies for Energy Management 1996).

According to the latest information (Carmichael et al. 1997) the beta testing of NIALMS is now going on. This commercial version of NIALMS for households consists of recorders and the host computer. The recorder measures current and voltage of the two power legs (typical power supply system for households in the US) and looks for stepwise changes in power usage as household appliances turn on and off and stores the data. Data are then periodically downloaded to the host computer. Communication between the host and recorder is via telephone line. The algorithm resides in the host computer. That keeps the costs down and make it easier to upgrade the software as the logic is improved. The host computer software uses matrix analysis by plotting the edge transition data on a Watt-VAR graph. Data from a single appliance tend to form clusters. The clusters are then compared to a software library of appliance signatures. When a cluster is matched with a stored signature, an identification is made. This way the load data is disaggregated and reports of individual appliance energy consumption as well as the trend of the whole house power usage can be obtained. One recorder will cost $ 1200 and a host computer system (a high-powered PC) that can accommodate about 300 recorders will cost $ 15,000.

Work is also going on to develop a monitoring system for commercial buildings (EPRI 1995). The system (C-NILMS) will be designed for 3-phase service for metering points of less than 100 kW. The hardware prototype will be similar to the residential unit. Load identification will be extended using harmonic signatures. At the same time Dr. Steven Leeb of MIT's Electrical Engineering Department is extending the non-intrusive detection algorithm to include transient detection.

1.1.2 France

Electricite de France (EDF) has engaged in some studies since 1990 whose aim is to recognize domestic electrical uses (Sultanem 1991). The basic monitoring principle is the same as in the US: to recognize active/reactive step changes in the total load produced by the starting and stopping of the different appliances of the customer. In a collaboration with Schlumberger Industries, a digital prototype of a recorder was built during 1989 - 1992. The device, named ACNI, fed by the currents and voltages of a single phase customer records dP and dQ each time a variation of the load is detected. A software developed by EDF for an off-line PC, reads the recordings and is able to classify them in different categories using a customization technique. Schlumberger has been investigating another approach which is based on a neural network.

Currently at EDF a new approach is under investigation. It consists of a Hidden Markov Model (HMM) which attempts to recognize the logical and chronological switch-on and switch-off of different loads (Bons et al. 1994). HMModelling is a theory which has been intensively used for speech recognition. An HMM consists of states and transitions between those states. Probability densities are associated with the transitions. For a given observation series, evolution through the states has to be guessed with the help of observation likelihood.

EDF has also equipped a laboratory with various domestic appliances. There the electrical signatures of these appliances (P,Q, also harmonic currents and transients) can be recorded and stored in a data bank and prototypes of NIALMS can be tested.

1.1.3 Other countries

In Denmark DEFU and the Danish Technical University carried out a research project during 1990 - 92 which was based on the use of Fuzzy logic to recognize household appliances. The results were unsuccessful mainly because of the lack of suitable 3-phase load registration equipment. In Denmark, as in Finland, a major part of the households have a 3-phase power supply. The Danish researchers noticed that when recording small appliances together with relatively large appliances precise equipment will be needed. In households most appliances have a small consumption of reactive power (Q) compared to the active power (P) and this demands high precision for the detection of Q.

In Finland, at VTT Energy, a research and development project of NIALM has been going on since the end of 1993. The results of this project will be presented in this work. The English terminology of NIALM used in this work is based mainly on professor Hart's presentations (Hart 1992).

1.2 EDEVE CO-OPERATION IN EUROPE

At the beginning of 1995 three international working groups of different load research subjects started in Europe. The common name of the coordination group is EDEVE (**E**DF/France, **D**EFU/Denmark, **E**FI/Norway, **V**TT Energy/Finland, **E**lectricity Association/United Kingdom). One working group is concentrating on intrusive and non-intrusive load monitoring systems. The purpose of these groups is to share experiences in different countries, to exchange data and to form bigger research and development projects.

1.3 GOALS

In principle there are two main NIALM goals depending on the degree of non-intrusiveness. The more intrusive one called Manual-Setup NIALM (MS-NIALM) is a system, which requires a one-time intrusive period for setup. During the intrusive setup period signatures are observed and named as appliances are manually turned on and off. It is distinguished from conventional intrusive instrumentation in that no hardware is ever installed on the premises being monitored. The less intrusive one called Automatic-Setup NIALM (AS-NIALM) sets itself up as it measures the load, using prior information about the characteristics of possible appliances. It must determine the signatures, and name the appliances with which they are associated without the benefit of any entry or appliance survey.

The first step is to develop an MS-NIALM. An AS-NIALM is more ambitious technically and its development requires the basic data gathered with MS-NIALM. MS-NIALM is more accurate than AS-NIALM but the total non-intrusiveness of the last one makes it very attractive from the users' point of view. It can be assumed that a fully AS-NIALM system could be developed only for residential applications because of the similarity of appliances in homes. In the premises of bigger electricity consumers the only realistic possibility in the near future is MS-NIALM. The goal of this work is to present a new MS-NIALM system based on a modern three-phase kWh-meter which can be applied to many kinds of consumers.

2 RECORDING SYSTEM

Traditional load monitoring instrumentation involves complex data-gathering hardware but simple software. A monitoring point at each appliance of interest and wires (or power-line carrier techniques or radio signalling) connecting each to the central data- gathering unit provide separate data channels, and the software only tabulates the data arriving over these separate hardware channels. In the NIALM-system this is reversed: simple hardware and complicated software. Only a single point in the installation is monitored, but mathematical algorithms have to separate the measured load into separate components. This chapter deals with appliance signatures and the monitoring hardware which are closely related to each other. The hardware developed in the US is described in the Patent. US (4858141).

2.1 APPLIANCE SIGNATURES

The role of appliance signatures are the essence of the NIALM. Generally, an appliance signature can be defined as a measurable parameter of the total load that gives information about the nature and operating state of an individual appliance in the load. Signatures can be divided into intrusive and non-intrusive signatures. Only the last ones are considered in this work. A non-intrusive signature is one which can be measured by passively observing the normal operation of the load, e.g., a step change in the measured power. Within the non-intrusive signatures there is a natural dichotomy according to whether information about the appliance state change is continuously present in the load as it operates ("steady-state signatures") or only briefly present during times of state transition ("transient signatures")(Hart 1992).

2.1.1 Steady-state or event signatures

Steady-state signatures derive from the difference between steady-state properties of operating states, calculated as the difference of powers between the operating levels of the connected states (dP, dQ in Fig.1). Steady-state signatures are much easier to detect than transient signatures. The sampling rates and processing requirements necessary to detect a step change in power are far less demanding then those required to capture and analyze a transient current spike. In the following a step change in power or the transition of an appliance's operating state to another state is labeled as an *event* and in an analogous way equipment able to detect these events is called an event recorder. An event recorder provides information about a larger number of state changes than a transient recorder because most appliances which generate a transient at turn-on generate no transient at turn-off.

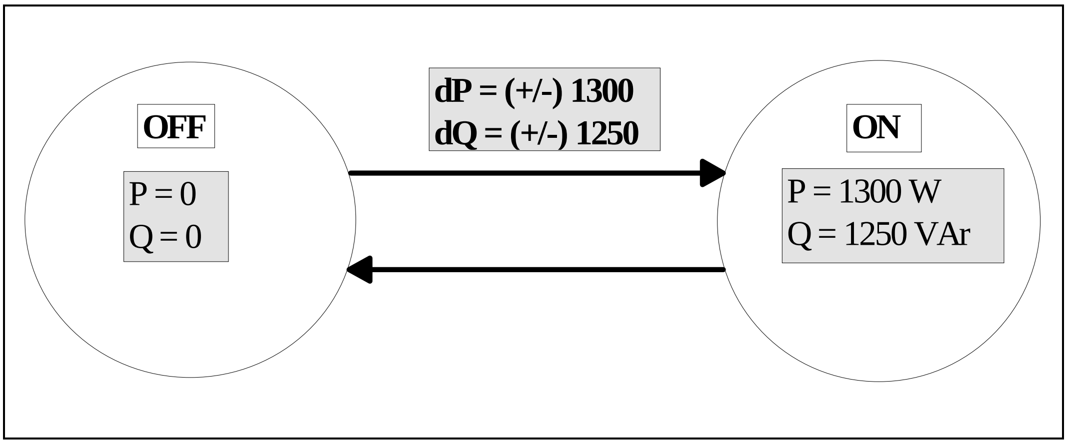

Fig. 1. An example of the operating states and state transitions of a two-state appliance (one on- and one off-state).

Event signatures can be divided into two categories: fundamental frequency (50 Hz in Europe, 60 Hz in the US) and harmonic frequency signatures. Many motors have a triangular current wave form which contains significant third, fifth, and other low-order odd harmonics. Many electronic power supplies generate a current spectrum rich in harmonic components at higher frequencies. Fluorescent lighting has a very high generation of the third harmonic of the current. Resistive loads and incandescent lights don't produce harmonics. Recording harmonic frequency signatures requires much more expensive equipment than the recording of fundamental frequency signatures. In this work only the fundamental frequency signatures are considered because the kWh-meter manufactured by Mittrix used as an event recorder has a low sampling rate and therefore it is not able to separate signatures of harmonic frequencies.

The utility voltage fluctuates over time meaning that U is not constant but is time dependent: $U(t)$. Voltage contains both gradual and step changes due to factors such as load dependent voltage drops in transmission lines and tap-changing transformers. The actual voltage can vary within +/- 10 %. A linear device plugged into this varying voltage supply will draw a current which also varies +/- 10 %. The power consumption will then vary by over +/- 20 %. In order to get rid of this dependence and thus reduce the scattering within clusters, power must be normalized to a fixed benchmark voltage U_{ref} which is taken to be equal to the rated phase voltage (230 V) of the network according to the following formulas:

$$P_{norm}(t) = [U_{ref} / U(t)]^{2} \cdot P(t) = [230\text{ V} / U(t)]^{2} \cdot P(t) \qquad (1)$$

$$Q_{norm}(t) = [U_{ref} / U(t)]^{2} \cdot Q(t) = [230\text{ V} / U(t)]^{2} \cdot Q(t) \qquad (2)$$

Equations (1) and (2) can be generalized as follows:

$$P_{norm}(t) = [U_{ref} / U(t)]^{\alpha} \cdot P(t) \quad (3)$$
$$Q_{norm}(t) = [U_{ref} / U(t)]^{\beta} \cdot Q(t) \quad (4)$$

If an appliance obeys a linear model then $\alpha=\beta=2$. Table 1 (Hart 1992) shows the exponents found to give the most voltage-independent normalized power in the range between 115V and 125 V.

Table 1. Optimal normalizing exponents for individual appliances at 120 V.

	α (Real exponent)	β (Reactive exponent)
Coffee maker	2	-
Light bulb	1.5	-
Table fan	1.2	2.4
Refrigerator	0.7	2.9

Only the coffee maker seems to obey the theoretical value of 2. The water in the coffee maker stabilizes the temperature of the heating resistor, which keeps its resistance constant. In the case of a table fan and a refrigerator, one exponent is higher than average, the other is lower than average. Therefore it seems that normalization could be improved with non-integer exponents below 2 for the real portion of the load and above 2 for the reactive component. However it is still unclear, how far from 2 the values should be to optimize performance over the widest range of target appliances. Because of these uncertainties theoretical values $\alpha=\beta=2$ are used in the prototype NIALM-system described in this work.

The normalized powers described in equations (1) and (2) are used as input to the event detection algorithm which determines the times and sizes of all step-like changes. Fig. 2 shows an example of an on-event detection in a sample data. A key requirement here is that the procedure must not be affected by start-up transients which often accompany steps. The transient-passing step-change detector first segments the normalized power values into periods in which the power is steady and periods in which it is changing, as indicated by a two-dimensional power signature in Fig. 2. A steady or stabile period is defined to be one of a certain minimum length (e.g. time of two or three samples) in which the input does not vary more than a specified tolerance dP_{tol} and dQ_{tol} in any component and in any phase (3-phase system). The remaining periods, between the steady periods, are defined to be the periods of change. Consecutive samples in steady periods are averaged to minimize noise. A period of change is detected if a site-specific threshold dP_{tres} or dQ_{tres} is exceeded according to the following formula (P_i , P_{i+1} and Q_i , Q_{i+1} are successive samples):

$$| (P_i + P_{i+1})/2 - P_{i+3} | > dP_{tres} \quad (5)$$

$$| (Q_i + Q_{i+1})/2 - Q_{i+3} | > dQ_{tres} \quad (6)$$

If the threshold values are exceeded according equations (5) and (6) (the threshold is not compared with the difference of successive samples because some appliances switch on slowly and therefore a longer period is needed) and the steady period is found quickly according the following formulas,

$$| (P_{i+4} - P_{i+3}) | < dP_{tol} \quad (7)$$

$$| (Q_{i+4} - Q_{i+3}) | < dQ_{tol} \quad (8)$$

then the difference between the after-event and the before-event power values dP_{event} and dQ_{event} are defined as follows:

$$dP_{event} = (P_{i+3} + P_{i+4})/2 - (P_i + P_{i+1})/2 \quad (9)$$

$$dQ_{event} = (Q_{i+3} + Q_{i+4})/2 - (Q_i + Q_{i+1})/2 \quad (10)$$

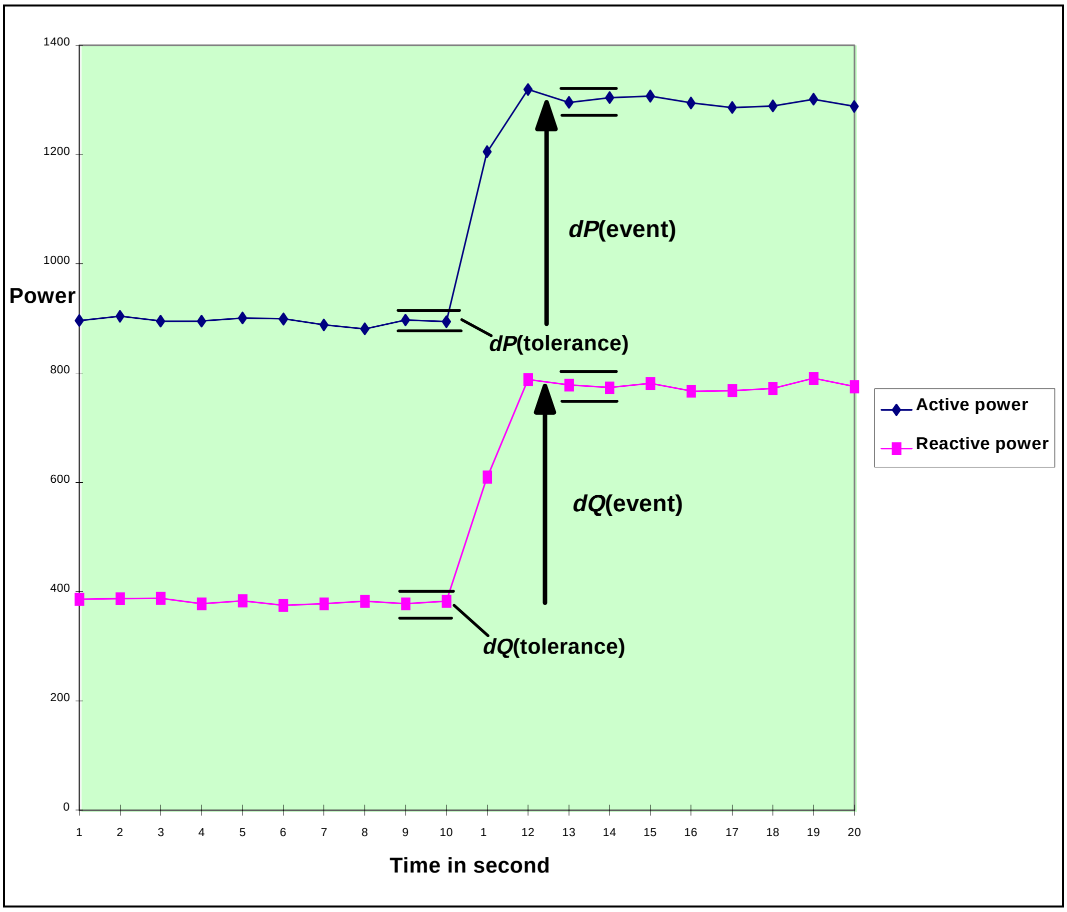

Fig. 2. Detecting an event in sample data caused by an appliance.

2.1.2 Transient signatures

Transient signatures are more difficult to detect and provide less information than steady-state signatures. However, they can provide useful information to augment that from steady-state signatures. For example, appliances having similar steady-state signatures may have very different transient turn-on currents. Analysis of the transient could provide the deciding information to determine which of the two actually is on in the total load.

Transients of appliances appear to come in different shapes, corresponding to the generating mechanism. Parameters for classifying transients are their size, duration and time constants. There exists some variability in transients of same appliances which depend on the exact point in the voltage cycle at which the switch opens or closes.

Resistive appliances typically have no transient when switching on, or a very short one (lower than 50 Hz period). Pump-operated appliances like electric motors driving a pump generate a long on-transient. Other motor-driven appliances (fans, washing machine, mixers) differ from pump-operated appliances by their generally less substantial switching on-transient. Electronically-fed appliances (televisions, video-recorders, PC) are characterized by a short but very high amplitude switching on-transient. Fluorescent lights have a long two-step switching on-transient.

In the following only steady-state signatures are considered because the Mittrix kWh-meter used as an event recorder has a low sampling rate and is not able to detect transient signatures.

2.2 DEVELOPMENT OF THE EVENT RECORDER

The starting point of this project was to test the suitability of the digital kWh-meter (type MXPQ) manufactured by the Finnish company Mittrix Oy the for NIALM-recorder. After the first tests it was clear that the standard version of this meter couldn’t measure reactive power accurately at small phase angles (angles less than 6 degrees, small Q and large P). In order to continue testing, one meter was calibrated specially: at the no load situation the phase angle between voltage and current was 8 degrees. This reset value was taken into account in the monitoring software. This way it was possible to determine if the relatively slow sampling rate of 128 samples/phase during a time interval of 940 ms of this Mittrix-meter was enough for non-intrusive recordings. Tests were successful and data collection for the development of the recorder software could start in the beginning of 1994.

The power consumed by a residence is preferably measured approximately every second. The exact rate is not critical to the non-intrusive method. A slower rate can be used, but this probably leads to more errors in identifying appliances. A slightly higher rate means more expensive recording devices and there is no apparent advantage in exceeding, for example, ten measurement per second.

2.2.1 Power quality monitoring kWh-meter

At the same time VTT Energy, Mittrix Oy and some Finnish power companies began to develop a remotely readable kWh-meter that should also be able to monitor power quality in the distribution network. In that project the idea was not to plan a totally new meter but to add features that measure the factors determining power quality to an existing remotely readable meter (type MXPQ) with free data processing capacity (Koponen et al. 1996). The purpose was to avoid any hardware modifications, because one aim was to keep the price of the meter as low as possible. That was a restriction during the planning and choosing phase as to what kind of power quality measurement features it was possible to implement. During the specification phase the requirements of NIALM was also taken into account in order to develop a real multipurpose meter. Especially the measurement of reactive power was carefully considered. Generally, the following formulas can be written which describe the relationship between different reactive powers (single phase case):

$$Q_F^2 = S^2 - P^2, \tag{11}$$
$$S = UI, \tag{12}$$
$$U^2 = \sum U_h^2, \tag{13}$$
$$I^2 = \sum I_h^2, \tag{14}$$
$$Q_F^2 = Q_{1f}^2 + Q_H^2, \tag{15}$$
$$Q_{1f} = U_{1f} I_{1f} \sin\varphi_{1f}, \tag{16}$$

where

I current RMS value
I_h harmonic current of order *h*
I_{1f} fundamental frequency current
φ_{1f} fundamental frequency phase angle
Q_F reactive power (Fryze's reactive power)
Q_H non-fundamental reactive power
Q_{1f} fundamental frequency total reactive power
P total active power
U voltage RMS value
U_h harmonic voltage of order *h*
U_{1f} fundamental frequency voltage
S apparent power.

The standard meter measures Fryze's reactive power Q_F and active power P. The power quality meter (type MXPQL) is also able to measure fundamental frequency total reactive power Q_{1f} accurately at small phase angles also. Another reason to use Q_{1f} instead of Q_F in event recording is that fundamental frequency reactive powers are additive when different appliances are turned on and off. In order to simplify this presentation Q always means fundamental reactive power Q_{1f}. If this is not valid it is stated separately.

This developed kWh-meter consists of

- a measurement card/board which performs all the needed measurements of electricity and
- a data processing board, which processes the data from the measurement card according to the parametrisation done by the user and communicates with the reading servers.

The measurement card records for each phase 12 electrical quantities related to electrical billing and power quality. The measurement card sends each of these measured values once per second into a FIFO-memory. The data processing card reads the values from FIFO, stores them according to users choice and transmits them through the serial interface connection from where they can be read by a PC. A detailed discussion of the data management of the Mittrix-meter is presented in reference Saari et al. (1996). The power quality monitoring kWh-meter complies with the accuracy class 1.0.

2.2.2 Event recording system

The prototype event recording system consists of the power quality kWh-meter and a laptop personal computer (see Appendix 1). The meter is connected to power supply lines via current transformers in the electric distribution board of a building and to a laptop IBM-compatible personal computer via an RS-232 link. The meter sends, once per second, through the data link, registered measurement values to the PC and these values are processed and stored into the files of a hard disk.

The software developed for the laptop PC allows the user to choose the data format he wants to record. One possibility is to load one second data into files. One hour of second data is stored in one file. This type of recording requires much storing capacity and is typically used during the algorithm development phase.

Normally only events are detected. In this mode the site-specific thresholds - dP_{tres} and dQ_{tres} - are manually set before recording starts. Also the steady state power tolerances dP_{tol} and dQ_{tol} can be adjusted manually. The minimum value of the site-specific threshold power depends on the accuracy of the meter and the maximum value of the measured instant apparent power

S_{max}. If the accuracy is 1% and the maximum value of the instant apparent power S_{max} in one phase is 10 kVA then the minimum value of the threshold can be estimated to be $0.01 \cdot S_{max}$ = 100 W or 100 Var. A good experimental estimate for steady state power tolerance is about 0.3 % from S_{max}. In the above example it will be $0.003 \cdot S_{max}$ = 30 W or 30 VAr.

In the event recording mode the following magnitudes are recorded and loaded into a file to process further later on:

- date and time of starting the monitoring
- time of events t_i from start, i=1,...,m m = number of measured events
- duration of change period t_{i+x} - t_{i+1} , t_{i+x} = time stamp of first steady sample after the event
- real before-event power in every phase (P_{ij} + $P_{(i+1)j}$)/2, j=1...3
- reactive before-event power in every phase (Q_{ij} + $Q_{(i+1)j}$)/2, j=1...3
- real power change in every phase $dP_{(\text{event})j}$, j=1...3
- reactive power change in every phase $dQ_{(\text{event})j}$, j=1...3.

The resulting “signature space” is a six-dimensional space (real and reactive power changes of three phases). Processing the recorded data further, the space will increase to eight-dimensional (real and reactive power changes of three single phases and one symmetrical three phase). This analysis will be discussed later in chapter 4.

Voltage values in every three phase and total power data are also preserved in another file at 15 minute average values. Voltages are used for “unnormalizing” the power of appliances and total power is used in calculating e.g. the “residual energy”.

The recording software has a special property which enables the user to detect and to load names of individual appliances into files when these appliances are switched on or off. This helps considerably when the difficult task of appliance naming during data analysis is performed.

3 LOAD MODELS

3.1 TOTAL LOAD MODEL

Appliances are electrically wired parallel on power lines (Fig.3). Each load is indicated by the symbol *Y*. Admittance (*Y*) is preferred as an appliance identifying parameter since it has a value which is more independent of line voltage variations than other possible choices of electrical parameters, such as power, current or reactive power. It is also additive, in a way that the admittance of appliances operating in parallel is equal to the sum of their individual admittances. Admittance (*Y*) is the vector sum of the conductance (P/U^2) and susceptance (Q/U^2). Multiplying these values by the square of a fixed benchmark voltage (rated phase voltage 230 V) we get the formulas of $P_{norm}(t)$ (1) and $Q_{norm}(t)$ (2).

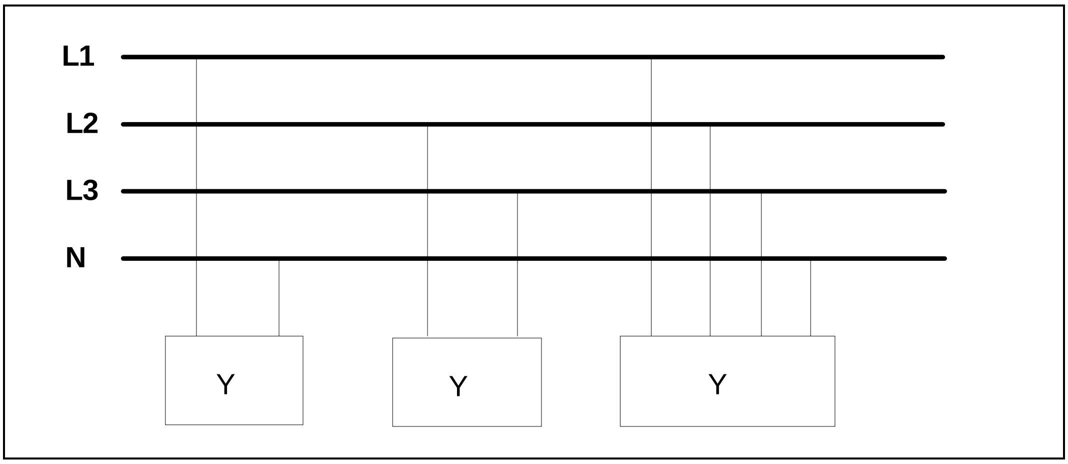

Fig. 3. Different possibilities to wire appliances (Y) on power lines in a three phase system (L+N, L+L or L+L+L+N).

In order to decompose the total load into its components, models of individual appliances and their combinations will be needed. The total load depends on how many appliances are on at any given moment. Supposing n on/off-appliances in a setting; we get a switch process $s_k(t)$, k = 1...n ($s_k(t)$ = 1, if appliance k is on at time t and $s_k(t)$ = 0, if appliance k is off at time t). For k = 1...n, let $\boldsymbol{P}_k$ be the p-vector of the power that the kth appliance consumes when it operates. For a three-phase system each $\boldsymbol{P}_k$ is a three-component complex vector. The real and imaginary parts of the vector in the jth component of the vector correspond to real and reactive power consumed in the jth phase. Two of the three components are zero for single phase appliances; one of the components is zero for two phase appliances and the three components are equal for symmetrical three phase appliances. According to the above definitions we get the following model (Hart 1992):

$$P(t) = \sum_{k=1}^{n} s_k(t)P_k + e(t) \qquad (17)$$

where $P(t)$ is the measured power as seen at the utility at the time t, and $e(t)$ is a small noise or error term.

From the model (17) we can try to determine the state functions $s_k(t)$ of the appliances. If all the P_k's are known, and the power $P(t)$ has been measured, then we can for each t solve the n-vector $\boldsymbol{F}(t)=[s_1(t),...,s_n(t)]$ from the optimization problem

$$\min \left| P(t) - \sum_{k=1}^{n} s_k(t) P_k \right| \quad (\forall k)\ \ s_k(t) \in \{0,1\} \qquad (18)$$

If this problem can be solved mathematically, there are a number of difficulties in estimating $\boldsymbol{F}(t)$. The fundamental problem with the approach of (18) is that the complete set of $\boldsymbol{P}_k$ is never known. If equation (18) were used in the presence of unknown appliances, it would spuriously to attempt to describe their behavior as a combination of other known appliances.

Another big problem in using (18) is that a small change in the measured power $P(t)$ would often be analyzed as a big change in the switch process $s(t)$, meaning that many appliances change state in a short period. This is not a probable situation in a real home or building because of the physical independence of different appliances. This leads to the following criterion called *Switch Continuity Principle* (SCP) according to professor Hart (Hart 1992):

In a small time interval, we expect only a small number of appliances to change state in a typical load.

Perhaps model (18) could be modified for NIALM applications by adding a term to the right-hand side proportional to the number of state changes in $\boldsymbol{s}(t)$ in order to follow SCP. Because of many apparent difficulties in the approach (18) it has not been investigated in this work. It was presented here in order to point out its difficulties and because it may be appropriate for similar problems in which the SCP principle is less important and the set of $\boldsymbol{P}_k$ is fixed and completely known.

3.2 APPLIANCE MODELS

Appliances that can be detected non-intrusively are classified into two main groups:

- on/off or two-state appliances (Fig 4a)
- multi-state appliances (Fig 4b).

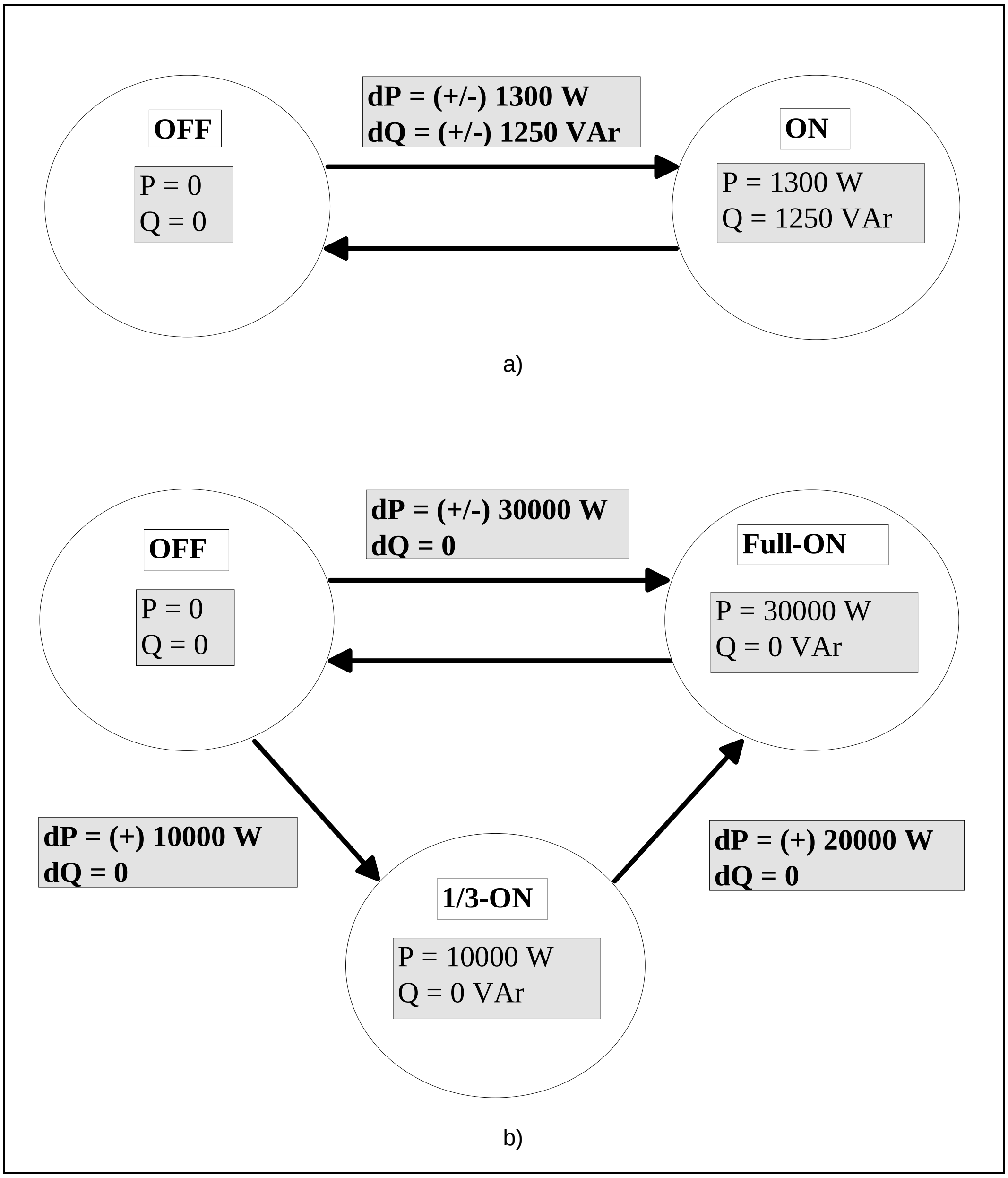

Fig. 4. Finite-state appliance models: a) generic two-state appliance, water pump b) multi-state appliance, hot water boiler.

Two-state or on/off appliances have only one transition power value (dP_{tr}, dQ_{tr}) and two power-states (0,0) and (P_{ON}, Q_{ON}). The value of transition power is always equal to the one at the on-power state, which means that

$dP_{tr} = P_{ON}$ and $dQ_{tr} = Q_{ON}$ (Fig. 4a). Most appliances in a household are two-state appliances and also appliances which contain several individual loads, such as motors and resistors, which can be considered as on/off-appliances. This is the situation for example in the case of a dishwasher. Some washer types consist of a thermostatically controlled heating resistor, motors for circulating water and pumping water away. All these individual loads can be considered as two-state appliances and identified separately because they switch on and off independently and they don't form transition powers which are combinations of each other (Fig 5).

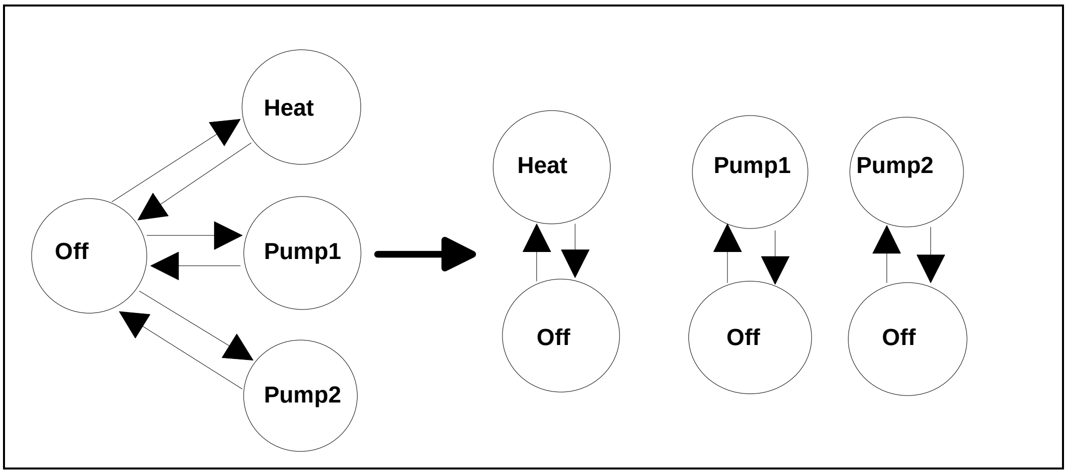

Fig. 5. Breaking a model of a dishwasher into many two-states models.

A more complicated situation arises in the case of a typical clothes washer which has a thermostatically controlled heating resistor, a water pump motor and a winding motor of the drum. Fig. 6 shows how the total model consists of two-state and combined power models. The last ones are results of simultaneous events which appear when the heating resistor and the drum motor switch on or off simultaneously. This can happen very often because the drum reverses its direction of rotation frequently. These combined powers can vary over a wide range if the motor has many different operating power levels like the one in Fig. 11.

Multi-state appliances have more than one on-state and the state powers are combinations of transition powers. Fig. 4b shows a simple example from an appliance which has three power states. It is a hot water boiler in an accumulating electrical heating system, which is remote-controlled in steps by the utility and locally by a thermostat. In the evening the utility first controls with 10 kW on and after two hours 20 kW more on. The thermostat controls with 30 kW on and off.

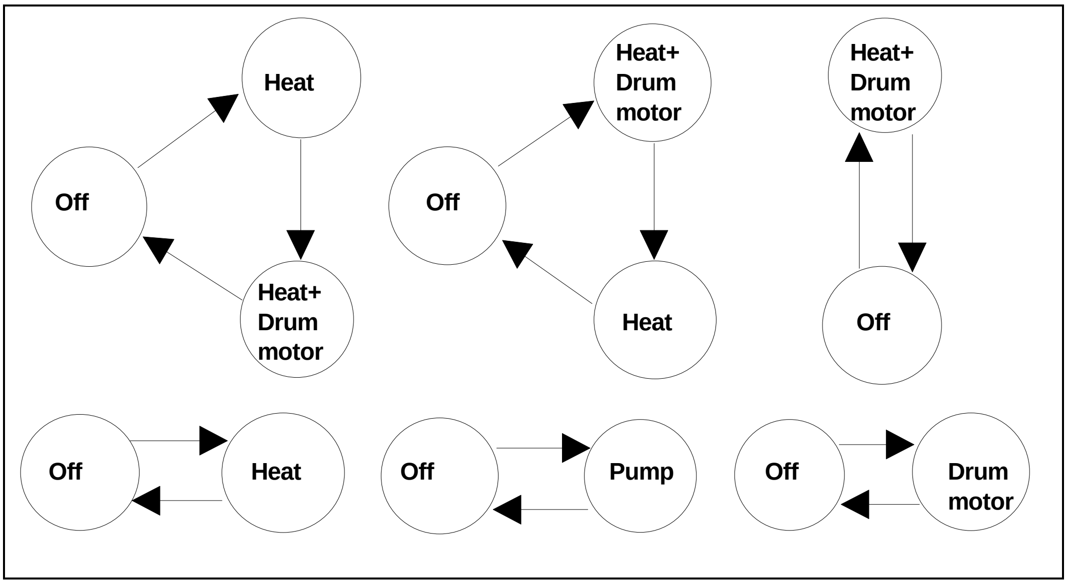

Fig. 6. Model of a typical clothes washer.

A more complicated multi-state model is presented in Fig. 7. It describes a four-state appliance, which is controlled by push buttons. Every state can be transferred to any other state.

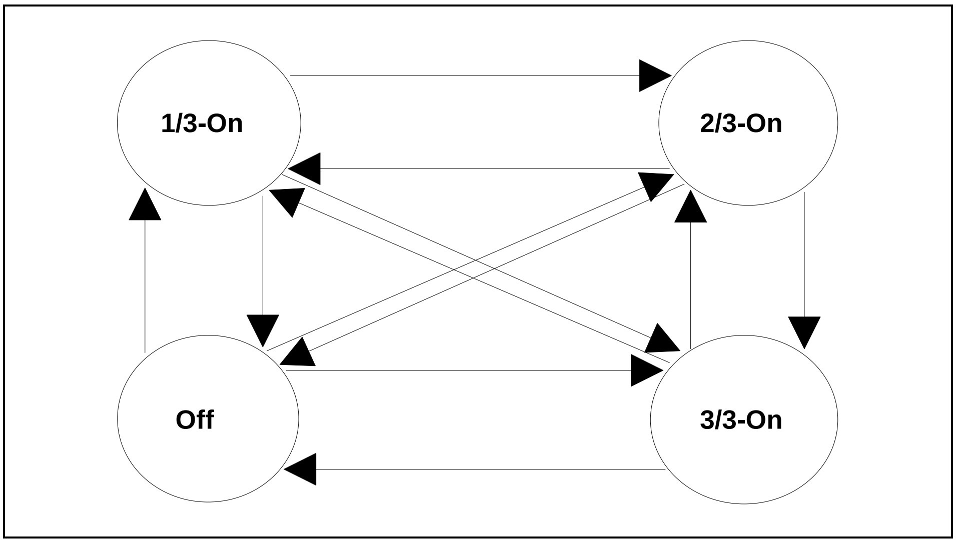

Fig. 7. Model of an appliance controlled by push buttons.

A very complicated example of multi-state appliances is an electric range in a household. It normally consists of four hot-plates most of them controlled manually and e.g. one hot-plate controlled by a thermostat and an oven controlled by a thermostat. Table 2 shows an example of different power and power transition states of manually controlled hot-plates. In this case the power signature of the thermostatically controlled hot-plate is dP=2333 W, dQ=0 and the signature of the oven is dP=2268 W, dQ=0. In principle the data in Table 2 can be described as similar to the model in Fig. 7, but the number of different states is much larger.

Table 2. Power states (W) of manually controlled hot-plates in a range (dQ =0, P_0=0, power off).

Power-states P_i (P_0=0, power off)	Small hot-plate		Medium hot-plate		Large hot-plate	
	$d(P_i-P_{i-1})$	$d(P_i-P_0)$	$d(P_i-P_{i-1})$	$d(P_i-P_0)$	$d(P_i-P_{i-1})$	$d(P_i-P_0)$
P_1	113	113	158	158	230	230
P_2	82	195	97	255	55	285
P_3	88	283	97	352	90	375
P_4	313	596	320	672	629	1004
P_5	277	873	279	951	360	1364
P_6	277	1150	844	1795	1013	2377

Fig. 8 shows non-intrusive measurement data of a range when it is used at home for cooking. Events are distributed along the d*P*-axis mainly between 600 W and 2400 W.

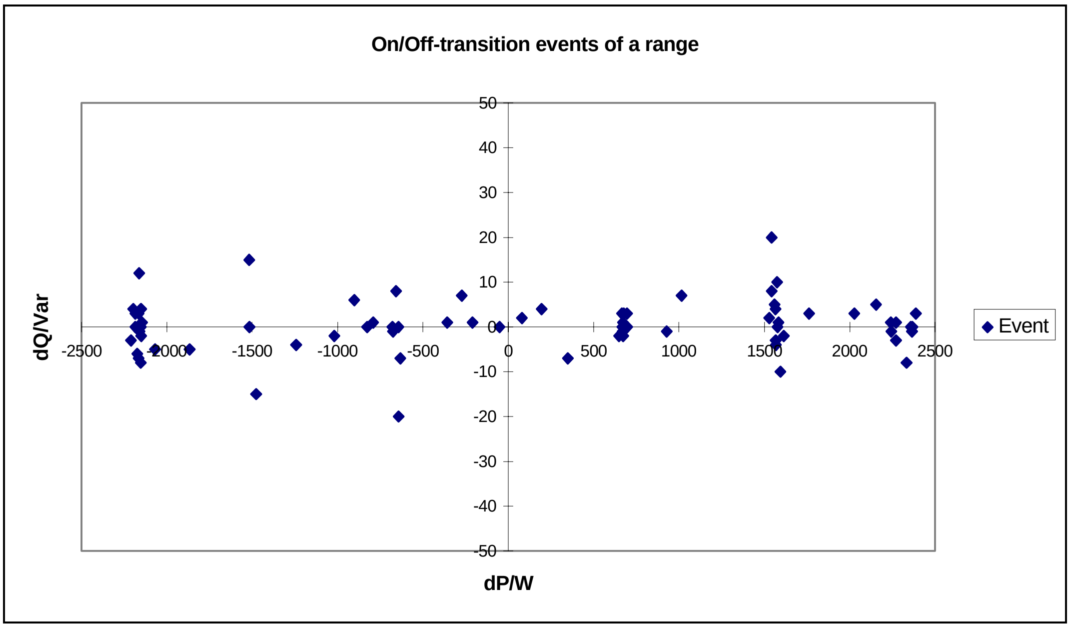

Fig. 8. Transition powers of a range.

The discussion in chapter 3.1 is only relevant to the on/off-appliances because the switch process *s(t)* allows that an appliance may be either on or off at any given time, but allows only a single type of on-state. This is an additional reason why model (18) is not used in NIALM-applications.

Appliances that should not be taken as targets of NIALM can be classified as follows:

- Appliances with very small power consumption
- Appliances which are always on
- Continuously variable appliances.

Small appliances cannot be measured because of noise in the recording equipment. Appliances that are always on can not be recorded because of missing signatures.

4 LOAD IDENTIFICATION ALGORITHMS

The whole NIALM system can be classified into different parts according to Fig. 9. It shows the hardware and main software components. The hardware components were discussed in chapter 2.2. The on-line analysis software components (normalization and edge detection) were discussed in chapters 2.1.1 and 2.2.2. In this chapter the off-line software components (modification of raw data, forming of appliance register and identification of loads) will be discussed. This analysis program was implemented by MS Visual Basic 5.0. It was found to be a suitable tool for calculations, graphical presentations and creating user interfaces for a non-intrusive appliance load monitoring system. The software allows the analysis of the measured data as many times as necessary in order to test different kinds of algorithms. Also the PC in the off-line analysis should be more powerful than the laptop PC at the measurement site.

4.1 MODIFICATION OF RAW DATA

In chapter 2.2.2 it was determined what magnitudes would be recorded during on line measurement. The following description is based on those definitions. R, S and T is the description of phase order applied throughout in this work. Every time during measurement, when an event occurs, the magnitude of this event and corresponding time stamp are stored in a file. The number of measured events either in single, two or three phases is denoted by *m*. The measurement values may thus be written in the following vectors:

$\boldsymbol{T} = (t_1, t_2,..., t_m)$	denote time of events from start of measurement
$d\boldsymbol{P}_R = (dP_{R1}, dP_{R2},..., dP_{Rm})$	denote real power events in phase R at time t_i,
$d\boldsymbol{P}_S = (dP_{S1}, dP_{S2},..., dP_{Sm})$	denote real power events in phase S at time t_i,
$d\boldsymbol{P}_T = (dP_{T1}, dP_{T2},..., dP_{Tm})$	denote real power events in phase T at time t_i,
$d\boldsymbol{Q}_R = (dQ_{R1}, dQ_{R2},..., dQ_{Rm})$	denote reactive power events in phase R at time t_i,
$d\boldsymbol{Q}_S = (dQ_{S1}, dQ_{S2},..., dQ_{Sm})$	denote reactive power events in phase S at time t_i,
$d\boldsymbol{Q}_T = (dQ_{T1}, dQ_{T2},..., dQ_{Tm})$	denote reactive power events in phase T at time t_i.

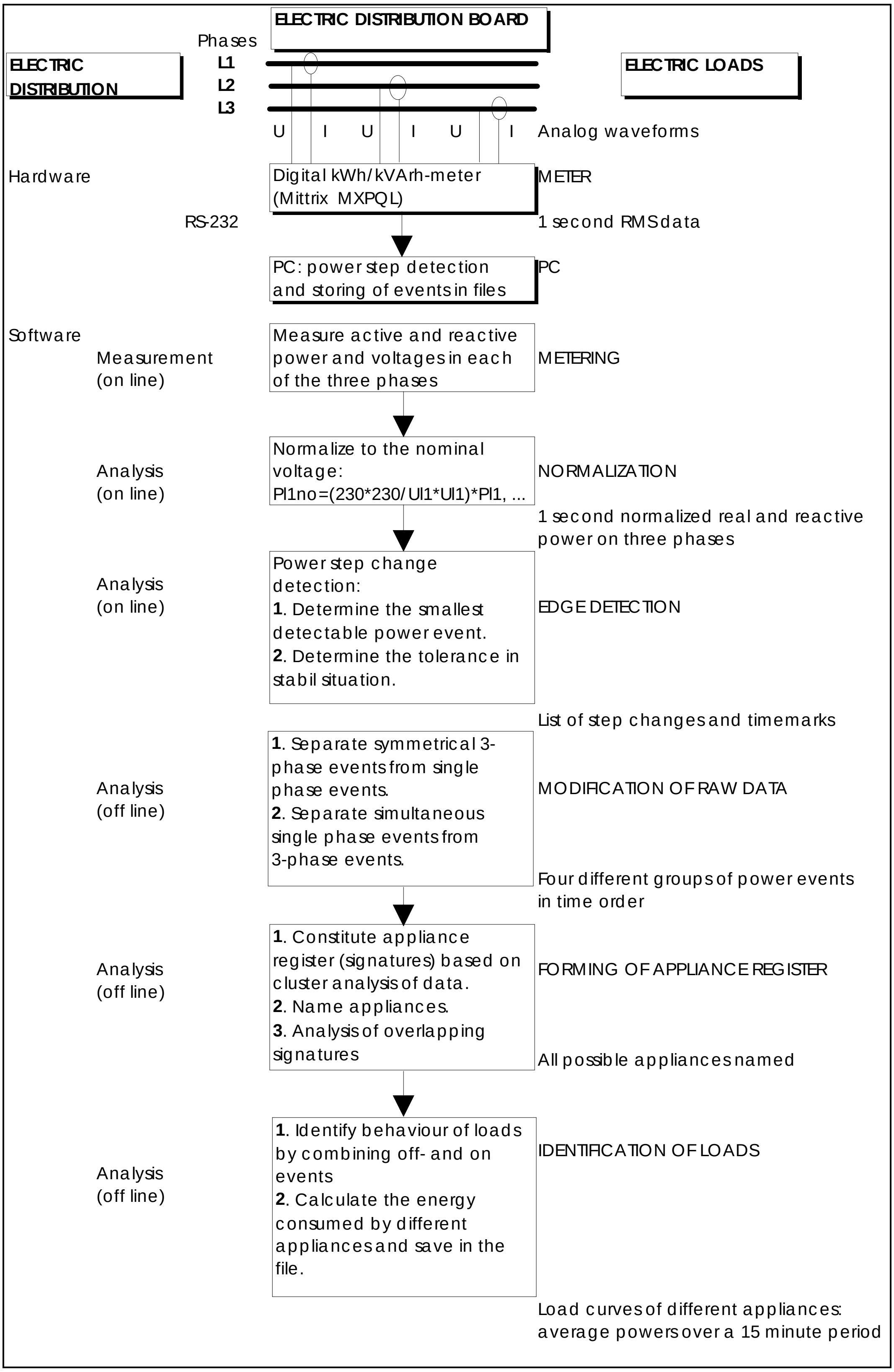

Fig 9. Hardware and software components of NIALMS.

This raw data includes simultaneous events, which can be considerably reduced by making use of different signatures of single and three-phase appliances. Most three-phase appliances are symmetrical (like motors) which means that $dP_{Ri} \cong dP_{Si} \cong dP_{Ti}$ and $dQ_{Ri} \cong dQ_{Si} \cong dQ_{Ti}$. Therefore if in all phases there occurs at time t an event > threshold then it can be: a symmetrical 3-phase load, or symmetrical 3-phase load + single phase load, or asymmetrical 3-phase load, or three separate appliances switching in different phases. If at the same time the magnitude of an event in one phase differs from the ones in the two other phases it is most probable that one single and one three-phase appliance have been switched simultaneously. Symmetrical 3-phase events and simultaneous 3- and single phase events can be separated successfully by using the following algorithm:

- One symmetrical 3-phase load at time t_i , if $0{,}9 \cdot |dP_{Ri}| \leq |dP_{Si}| \leq |dP_{Ti}|$ and $1{,}1 \cdot |dP_{Ri}| \geq |dP_{Si}| \geq |dP_{Ti}|$
- One symmetrical 3-phase load and single phase load in phase T at time t_i if $0{,}9 \cdot |dP_{Ri}| \leq |dP_{Si}|$ and $1{,}1 \cdot |dP_{Ri}| \geq |dP_{Si}|$ and $0{,}9 \cdot |dP_{Ri}| > |dP_{Ti}|$ or $1{,}1 \cdot |dP_{Ri}| < |dP_{Ti}|$
- One symmetrical 3-phase load and single phase load in phase S at time t_i if $0{,}9 \cdot |dP_{Ri}| \leq |dP_{Ti}|$ and $1{,}1 \cdot |dP_{Ri}| \geq |dP_{Ti}|$ and $0{,}9 \cdot |dP_{Ri}| > |dP_{Si}|$ or $1{,}1 \cdot |dP_{Ri}| < |dP_{Si}|$
- One symmetrical 3-phase load and single phase load in phase R at time t_i if $0{,}9 \cdot |dP_{Ti}| \leq |dP_{Si}|$ and $1{,}1 \cdot |dP_{Ti}| \geq |dP_{Si}|$ and $0{,}9 \cdot |dP_{Ti}| > |dP_{Ri}|$ or $1{,}1 \cdot |dP_{Ti}| < |dP_{Ri}|$.

The analysis concerning dQ_{Ri} , dQ_{Si} , and dQ_{Ti} will be performed parallel at the same time with the same algorithm. The +/- 10 % variance around the mean values arises from the difference of signatures in different situations (e.g. temperature of an appliance). Also noise and inaccuracy of measurement equipment results in some variation in detected events.

After this analysis the resulting "signature space" is eight-dimensional (real and reactive power changes of three single phases and one three phase). Thus the measurement can be written in the following vectors.

Phase R:
$\boldsymbol{T}_R = (t_{R1}, t_{R2},..., t_{Ra})$ — a is number of events > threshold in phase R
$d\boldsymbol{P}_R = (dP_{R1}, dP_{R2},..., dP_{Ra})$
$d\boldsymbol{Q}_R = (dQ_{R1}, dQ_{R2},..., dQ_{Ra})$

Phase S:
$\boldsymbol{T}_S = (t_{S1}, t_{S2},..., t_{Sb})$ — b is number of events > threshold in phase S
$d\boldsymbol{P}_S = (dP_{S1}, dP_{S2},..., dP_{Sb})$
$d\boldsymbol{Q}_S = (dQ_{S1}, dQ_{S2},..., dQ_{Sb})$

Phase T:

$\boldsymbol{T}_{\mathrm{T}} = (t_{\mathrm{T1}}, t_{\mathrm{T2}},..., t_{\mathrm{T}c})$ — c is number of events > threshold in phase S

$d\boldsymbol{P}_{\mathrm{T}} = (dP_{\mathrm{T1}}, dP_{\mathrm{T2}},..., dP_{\mathrm{T}c})$

$d\boldsymbol{Q}_{\mathrm{T}} = (dQ_{\mathrm{T1}}, dQ_{\mathrm{T2}},..., dQ_{\mathrm{T}c})$

3-phase RST:

$\boldsymbol{T}_{\mathrm{RST}} = (t_{\mathrm{RST1}}, t_{\mathrm{RST2}},..., t_{\mathrm{RST}d})$ — d is number of events > threshold in 3-phase RST

$d\boldsymbol{P}_{\mathrm{RST}} = (dP_{\mathrm{RST1}}, dP_{\mathrm{RST2}},..., dP_{\mathrm{RST}d})$

$d\boldsymbol{Q}_{\mathrm{RST}} = (dQ_{\mathrm{RST1}}, dQ_{\mathrm{RST2}},..., dQ_{\mathrm{RST}d})$.

All these four time-series of events with time stamps can now be analyzed separately.

4.2 FORMING THE APPLIANCE REGISTER

The appliance register contains information from those appliances which should be identified from the total load. The necessary data which should be available in this register is as follows:

- name of the appliance group to which an appliance belongs (like lighting, freezers, ...)
- appliance on and off- state transition powers (signatures): $dP_{\mathrm{ON}i}$, $dQ_{\mathrm{ON}i}$, $dP_{\mathrm{OFF}i}$, $dQ_{\mathrm{OFF}i}$
- appliance model (two or multi-state appliance)
- phase to which an appliance is connected (R, S, T or 3-phase)
- typical on-cycle time in seconds (<1800 sec, <3600 sec or >3600 sec).

On and off-state transition powers can differ from each other in absolute values because of a temperature rise during operation (heating elements) or special processes (cooling compressors). This can be utilized during identification.

Every state transition power in the register is given its own number and the appliances which belong to the same appliance group should be numbered one after another. All appliances which belong to the same group are added to form one appliance load curve. For example, an electric range can have very many state transition real powers and these powers are described in a register.

4.2.1 Adapting signatures and appliance names

One big problem is how to get the signatures and names of appliances for the appliance register. One possibility is to perform a one-time intrusive setup. During the intrusive setup signatures are observed and named as appliances are manually turned on and off (Fig. 10). It is distinguished from conventional intrusive instrumentation in that no hardware ever enters the premises being monitored. This is easy to perform if it is possible first to switch off appliances which cycle frequently. The recording software in the setup mode stops when it finds an event greater than the given threshold and allows the user to name this appliance. After this it continues recording and stops again when an event is detected. This way it is possible to gather the necessary data from main appliances in the monitoring site.

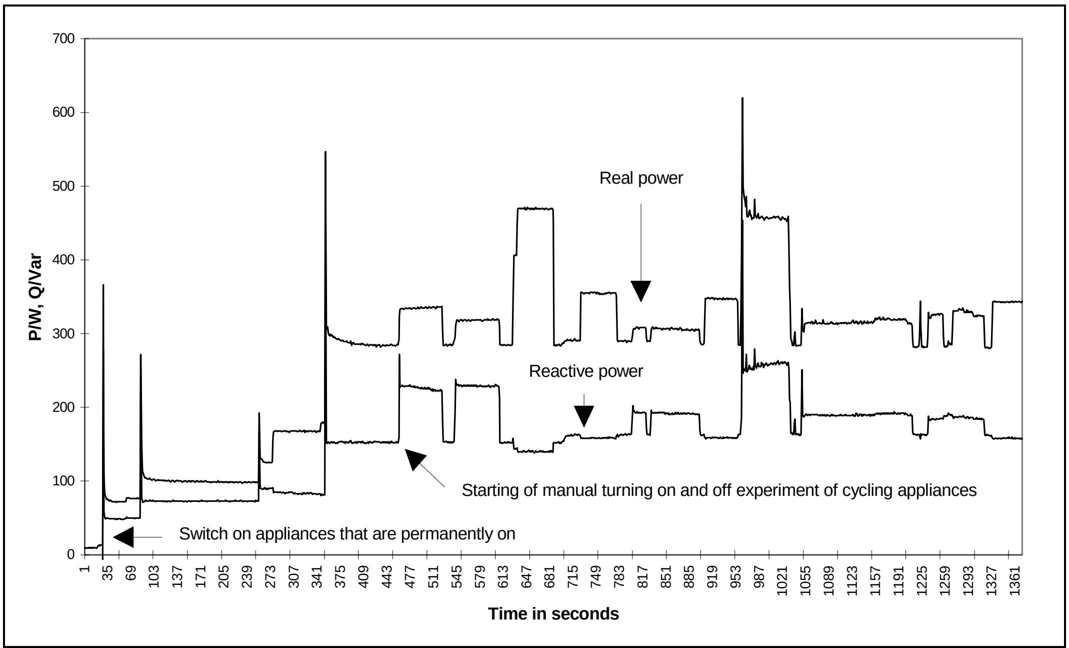

Fig. 10. Example of turning appliances on and off during setup period (the spikes during switch on appear because the first version of meters recorded Fryze's reactive power).

Another possibility is to perform cluster analysis of recorded data in order to find the on and off-signatures of appliances existing in the monitored building. Fig. 11 shows on and off-clusters of appliances in actual measurement data. Each group of points is supposed to contain events of the same appliance. The symmetry which appears on the plot is caused by the on-off behavior of almost all appliances; each positive power group (on-events) has to be related to a negative power group (off-events). The scattering within clusters depends on the type of appliance and the number of on or off-switchings. The cluster can be very wide like the one of an electronically controlled clothes washer. Also the accuracy of the recording equipment has an effect on the scattering within clusters. For example, in a household the total load often consists of big resistive loads and only some appliances have reactive consumption which is small compared to resistive loads. This means that when these resistive loads are switched on and a load having a reactive component switches on, the accuracy of detecting the reactive component of this event is not as accurate as detecting the real component because of the small phase angle of the total load. In this case the cluster will be wider in the direction of the dQ-axis than dP-axis.

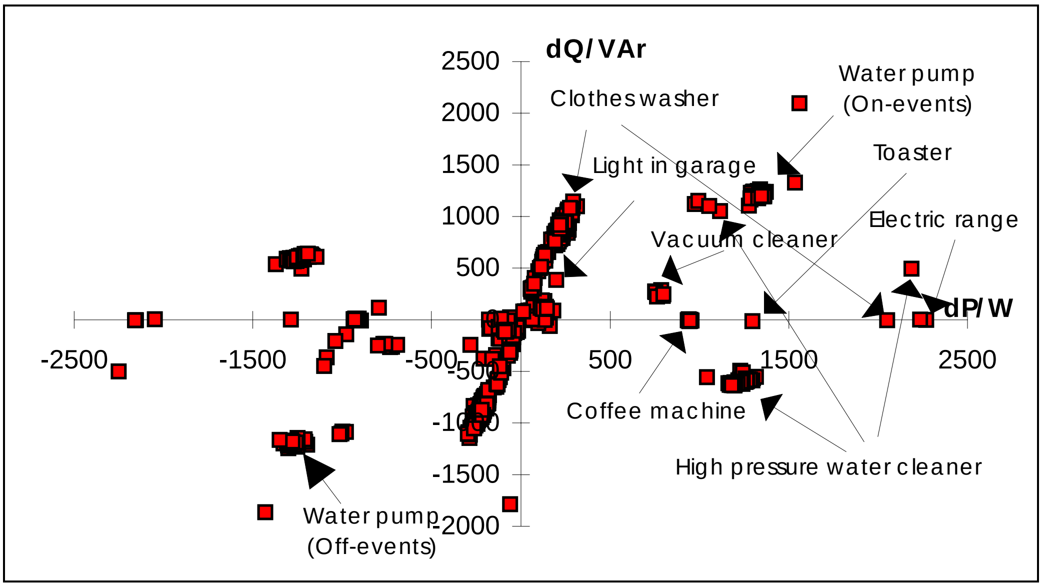

Fig. 11. Actual measurement data showing the scattering in appliance power on-off transition clusters (on the left of the dQ-axis, off-events, on the right, on-events).

Usually all on-events appear in the I-quadrant and off-events in the III-quadrant. Some appliances have signatures in both the II and IV-quadrant, like the high pressure water cleaner in Fig. 11.

A special software was developed which finds the mean values of appliance on and off-event clusters from all single phase and 3-phase events. After finding the mean values, the software combines suitable on and off-event signatures of the same appliance by taking into account the number of events in the on and off-clusters and the fact that the absolute values of the on and off-signatures are equal or off-values are 0...10 % smaller than on-values (as explained earlier in this section). The software shows these on and off-signatures based on recorded data and the user of this software is responsible for naming these appliances. He can for example use the data from the intrusive manual setup data file if it is available. After naming the appliance the software asks if it is a two or multi-state appliance and what the typical on-cycle time category of this appliance is. After this the software saves the above mentioned data and the phase (R, S, T or 3-phase), in which this appliance is connected, into the appliance register.

After this analysis we have an appliance register which describes the appliances of one monitored site. This register includes the signature vector of appliances $\boldsymbol{A}_i = (dP_{\mathrm{ON}i}, dQ_{\mathrm{ON}i}, dP_{\mathrm{OFF}i}, dQ_{\mathrm{OFF}i})$, $i = 1...n$, where n is the number of records in the appliance register. This number is equal to the total number of state transitions of all appliances in the register.

As mentioned earlier the scattering within clusters in the measurement data depends on many things. Before identification of loads is possible the deviation around the mean values of the signatures has to be determined. In this work they are fixed in the software according to the magnitudes of the transition active power signatures of an appliance (dP_i) based on experimentally determined limits from most commonly existing appliances. According to this method, the larger the active power signature is the wider the scattering allowed within this cluster is. The shape of this area around the mean value of the appliance signature power is chosen as a rectangle (Fig. 12).

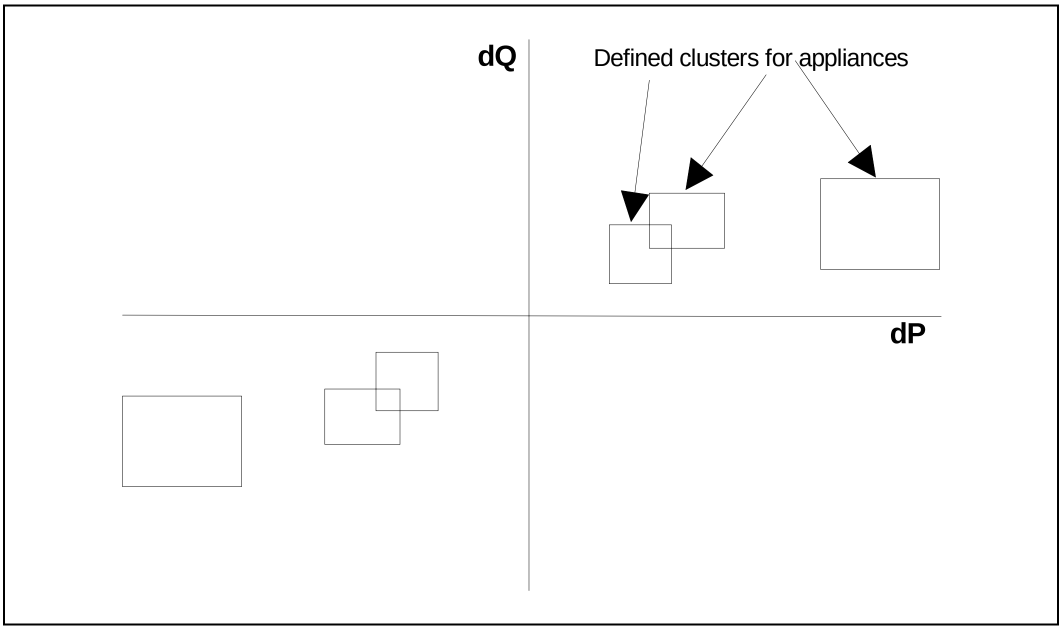

Fig. 12. Schematic view of scattering areas of power events around the mean values of signatures (left off and right on-events).

This means that if e.g. an appliance of 2000 W and another appliance of 60 W are switched on simultaneously in the same phase achieving a change of 2060 W this change is classified in the category of 2000 W and the event of the small appliance of 60 W is not identified. With this method appliances with large power consumption are identified more accurately than appliances with small power consumption. This seems to be reasonable because the purpose is to identify as big a part of the consumed electricity of appliances as possible from the total load.

4.2.2 Lights and small power appliances

In residences there exist a lot of appliances with small real power consumption. A good example is incandescent lamps. The power scale of individual lamps ranges from 25 W to 100 W (25, 40, 60, 75, 100 W). Because in many lighting units several lamps are installed together, the power of an individual luminaire can be whatever between 25 and 210 W. Also one switch can switch on and off more than one lighting luminaire at the same time. Fluorescent lamps are now available in both traditional and compact form, the latter often being designed to fit into a normal incandescent light socket. Therefore it is possible that combinations of incandescent and fluorescent lamps in the same lighting unit may be switched on and off with one switch. Also the power of portable plug-in lamps varies over a wide range. Fluorescent lamps with a power factor correction circuitry built into the ballast make the lamps appear as a nearly resistive load. So these small resistive lighting appliances don't have an individual cluster but the powers are scattered between 50 and 210 W along the d*P*-axis (Fig.13).

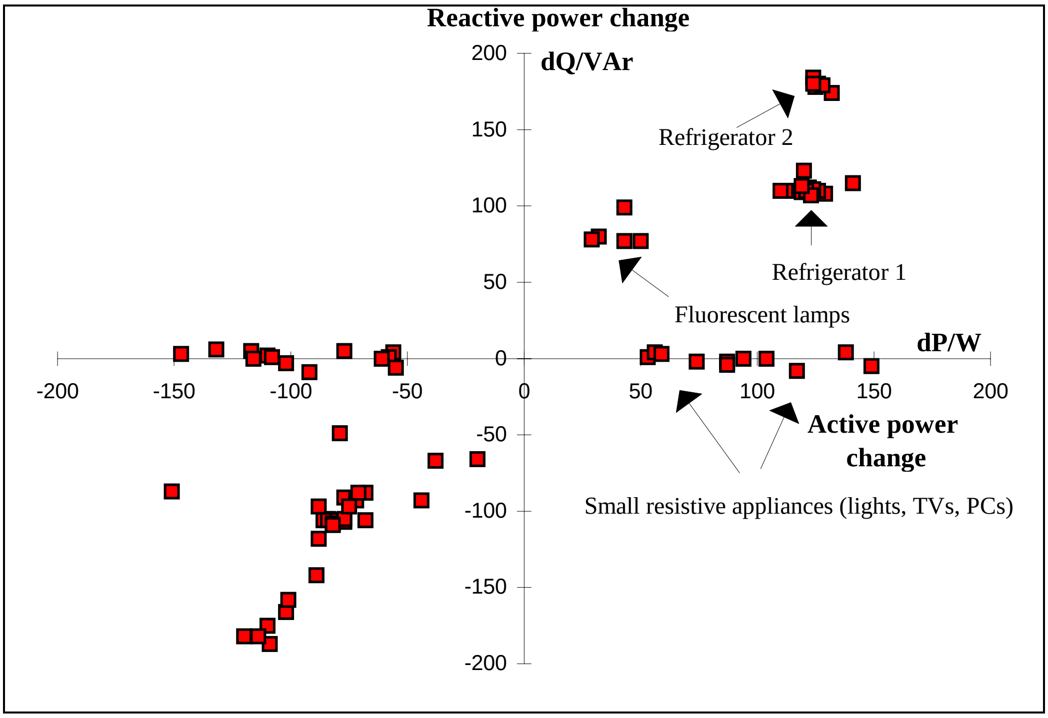

Fig. 13. Appliance on-off transition powers.

Unfortunately the common appliances in homes as television sets and personal computers also appear as nearly resistive load, because their fundamental frequency reactive power is very small apart from their total reactive power (Fig. 14). Therefore these appliances also have similar signatures as lights and they are classified together forming a group called small appliances in the appliance register. However this describes mainly lighting of incandescent lamps in residences because the number and total power of lights dominates over TVs and PCs. This group is available as an option automatically, every time a new appliance register is created by the software and controlled by the user. The identification algorithm cannot separate the load curve of electrically identical appliances, but it can estimate the total load curve of small appliances between 50 and 210 W. How this is performed will be explained later in chapter 4.3.4.

Clusters of common fluorescent lamps have their own typical area on the (dP,dQ)-plane (Fig 13). This area is defined in the appliance register automatically as the following square: 30 W ≤ dP ≤ 70 W and 70 VAr ≤ dQ ≤ 110 VAr (negative sign for off-cluster values respectively). Bigger fluorescent lights will be defined individually.

Signatures of freezers and refrigerators with small fans can be very close as shown in Fig. 14. Sometimes fluorescent lamps also overlap with small cooling compressors.

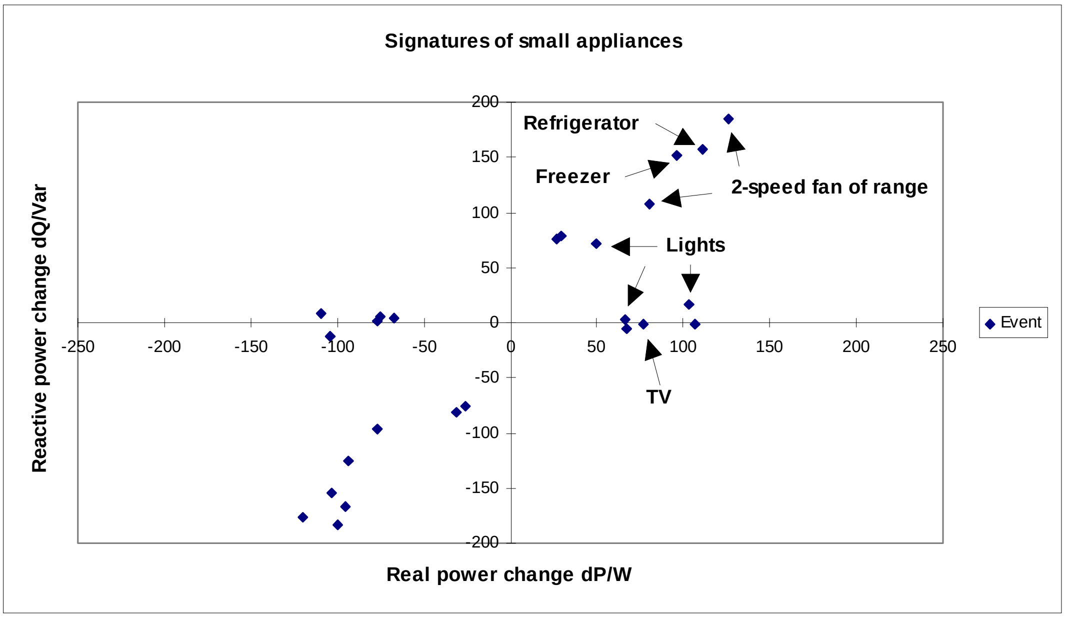

Fig. 14. Signatures of small appliances.

4.3 IDENTIFICATION OF DIFFERENT TYPES OF LOADS

4.3.1 Load identification software

Fig. 15 presents the main off-line software modules of the prototype NIALMS. As explained in chapter 4.1 the raw data was organized into four different time series (3 separate phases and symmetrical 3-phase). Every time series is analyzed separately with this identification software.

In this analysis an attempt is made to combine every off-event (dP,dQ; dP<0) with an on-event (dP,dQ; dP>0). The on-event or switch on of an appliance must be earlier in the time series than the off-event or switch off of the appliance. The connection of successive time series of data is done by adding the remaining on-events of the previous data file into the beginning of the next data file. This way it is possible to find the on-events corresponding to the off-events which appear in the beginning of a time series data file.

If the signature of an appliance corresponding to the considered off-event can be found from the appliance register then the on-event identification can start. In many situations the absolute value of an on-event is a little larger than the one of an off-event. This difference is described in the appliance register. If the off-event overlaps with two appliance signatures in the register then the information from phase order or maximum on-cycle time will be used in the identification. If the phase information doesn't help to distinguish between two appliances then an attempt is made to find the on-event of the appliance with shorter on-cycle time. If this doesn't lead to a good result then an attempt is made to find the on-event of the appliance with the longer on-cycle time.

The on-event identification process is done according to the appliance model. There are three different methods to perform identification. Two-state appliances are most common and have only one transition power (see 4.3.2). Multi-state appliances have at least two different transition powers (see 4.3.3). If there are many similar loads it is possible to combine these loads to a one-load curve by the algorithm explained in chapter 4.3.4.

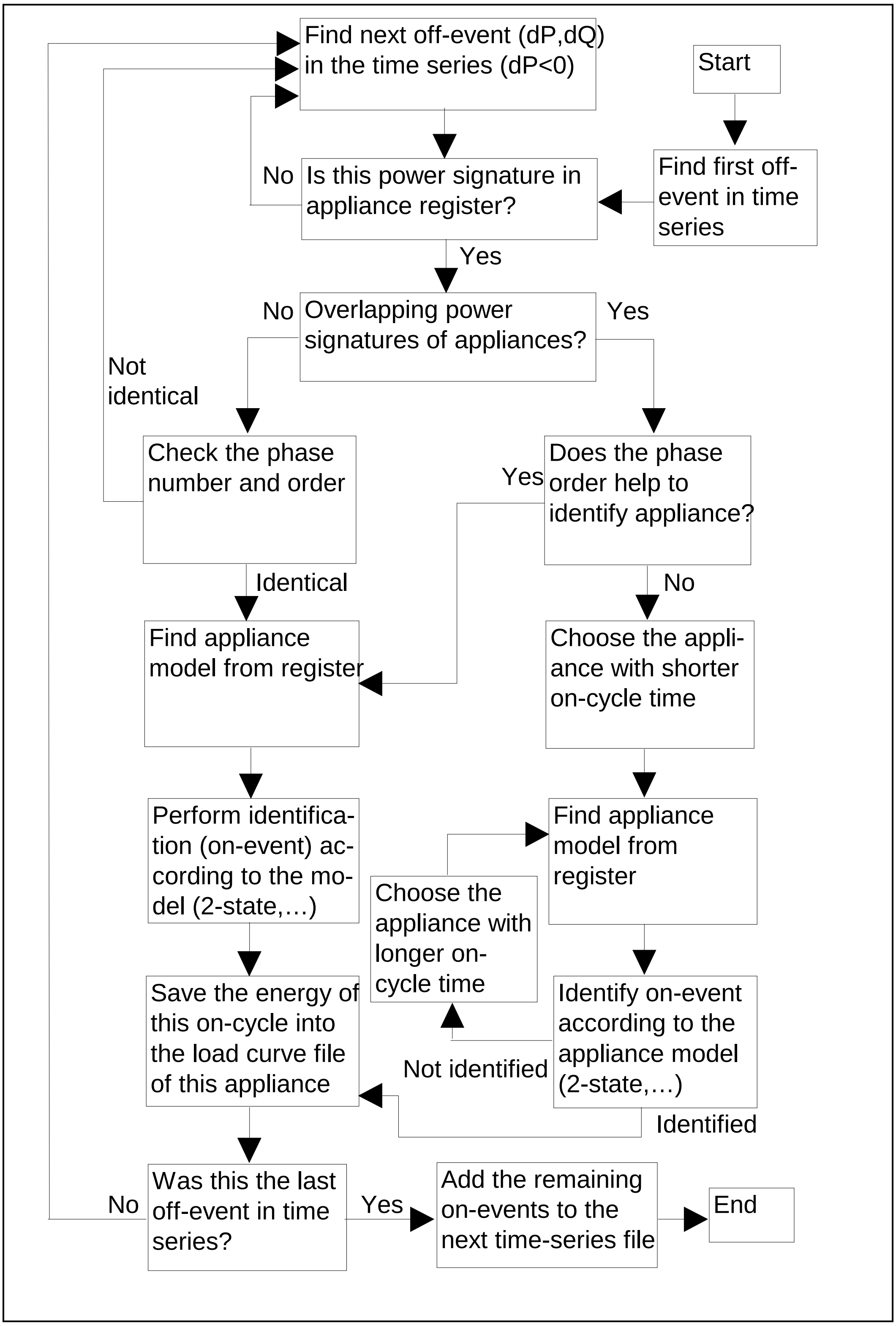

Fig. 15. Block diagram of load identification software.

4.3.2 Identification of two-state appliances

Fig. 16 shows an example of two different on/off-appliances switching on and off. Appliance 1 switches on at time t_1 and at power of dP_1 and switches off at time t_3 at power of dP_3. The total on-cycle time is $dT_1 = t_3 - t_1$. Appliance 2 switches on at time t_2 and at power of dP_2 and switches off at time t_4 at power of dP_4. The total on-cycle time is $dT_2 = t_4 - t_2$. During the identification process the off-power dP_3 is combined to the on-power dP_1 and the energy consumed by appliance 1 during time dT_1 W_{appl1} is calculated according to the following formula:

$$W_{appl1} = (|dP_3| + dP_1)/2 \cdot (U / U_N)^2 \cdot dT_1 \tag{19}$$

where

U is voltage during dT_1

U_N is nominal voltage 230 V.

Respectively the energy consumed by appliance 2 is

$$W_{appl2} = (|dP_4| + dP_2)/2 \cdot (U/U_N)^2 \cdot dT_2$$

where

U is voltage during dT_2.

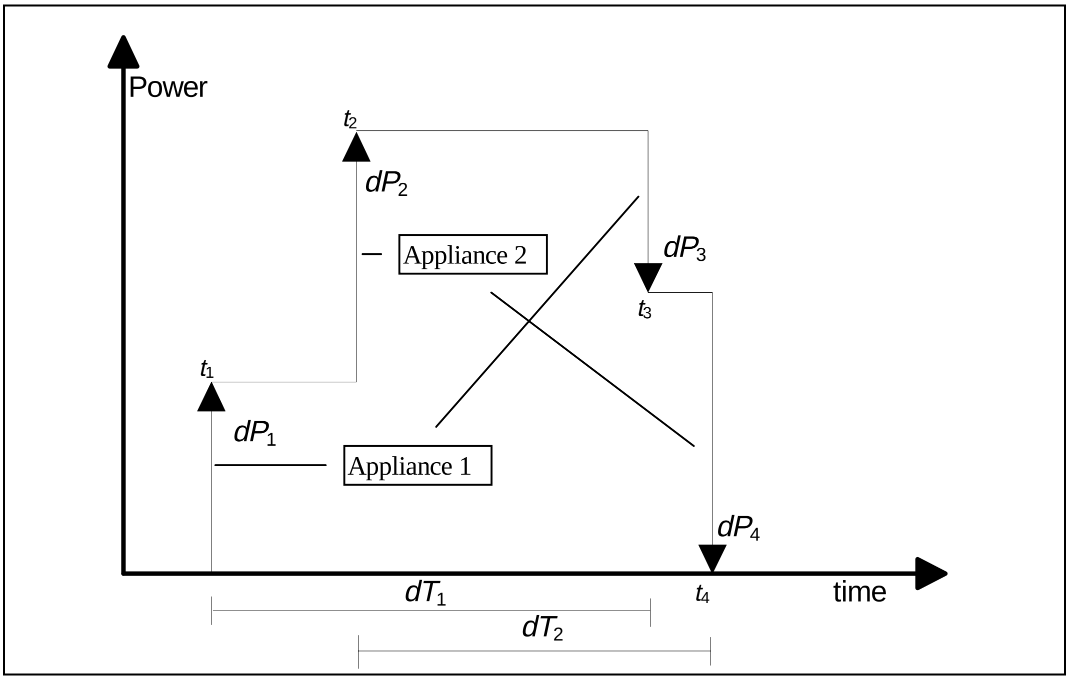

Fig. 16. Example of switching cycles of two two-state appliances.

4.3.3 Identification of multi-state appliances

Fig. 17 shows an example of switching cycles in a multi-state appliance. This appliance has three different on-transition powers (dP_1, dP_2, dP_3) and one off-transition power (dP_4). During identification process first dP_4 is compared to dP_3 which results in a new off-power dP_5 and then dP_5 is compared to dP_2 etc. We get the following virtual off-events: $dP_5 = dP_4 - dP_3$ and $dP_6 = dP_5 - dP_2$.

The whole on-cycle time (t_4 - t_1) divided into three different parts and the total on-cycle energy is calculated as follows:

$$W_3 = |\,dP_4| \cdot (U / U_N)^2 \cdot dT_3 \quad (20)$$
$$W_2 = |\,dP_5| \cdot (U / U_N)^2 \cdot dT_2 \quad (21)$$
$$W_1 = |\,dP_6| \cdot (U / U_N)^2 \cdot dT_1 \quad (22)$$
$$W_{total} = W_1 + W_2 + W_3 \,. \quad (23)$$

This procedure is independent of the number of on or off-power states of the appliance.

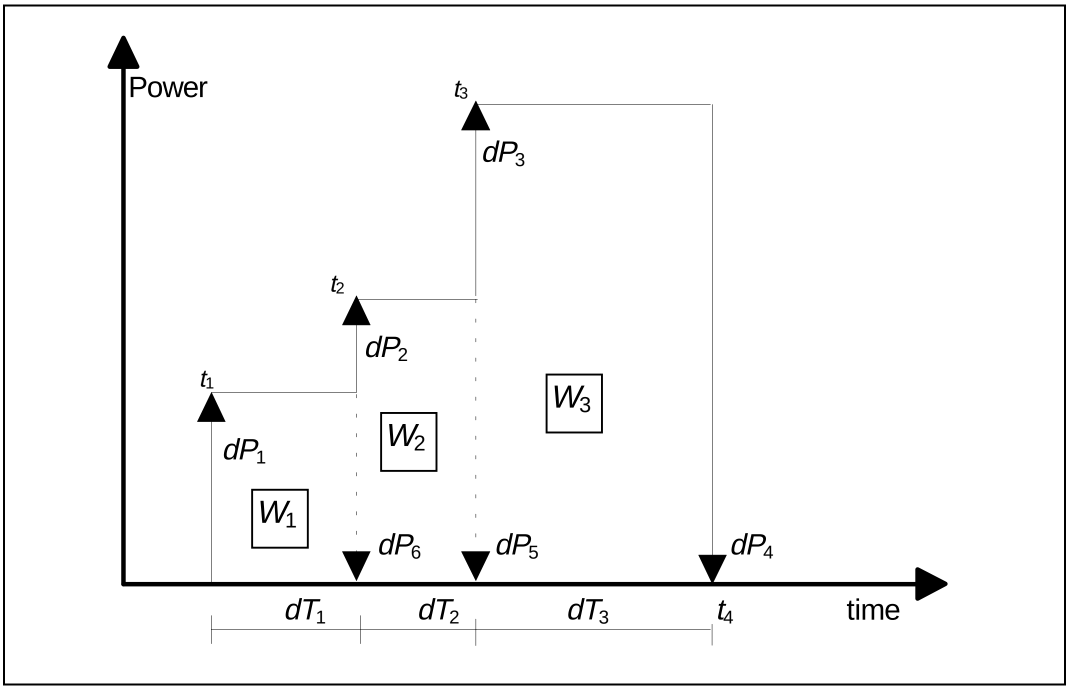

Fig. 17. An example of switching cycles of a multi-state appliance.

4.3.4 Identification of small appliances

Small resistive appliances in the power range 50 W < P < 210 W are grouped together with a special algorithm. In Fig. 18 a situation where small appliances are switched on and off is illustrated. Each off-event is combined to an on-event, which best fits the following conditions: the absolute value of each off-event (50 W < dP_{OFF} < 210 W) is compared to, a maximum of five, earlier possible on-events, if the condition $||dP_{OFF}| - |dP_{ON}|| < 25$ W is fulfilled. Finally those off and on-events, whose difference in absolute value is smallest, are chosen. This way it is possible to get an estimate of how small appliances are used although the combined off and on-events do not necessarily belong to the same appliance. This same algorithm can be used in a slightly modified form if attempting to identify two or more similar appliances in order to get one load curve.

In the case of Fig. 18 the algorithm would combine the following events: (dP_5, dP_3), (dP_6, dP_1), (dP_8, dP_4), (dP_9, dP_2), (dP_{10}, dP_7). Therefore the total energy consumption W_{tot} of all appliances in Fig. 18 is calculated the same way as in the case of two-state appliances as follows: $W_{tot} = (|dP_5| + dP_3)/2 \cdot (U / U_N)^2 \cdot (t_5 - t_3) + ... + (|dP_{10}| + dP_7)/2 \cdot (U / U_N)^2 \cdot (t_{10} - t_7)$.

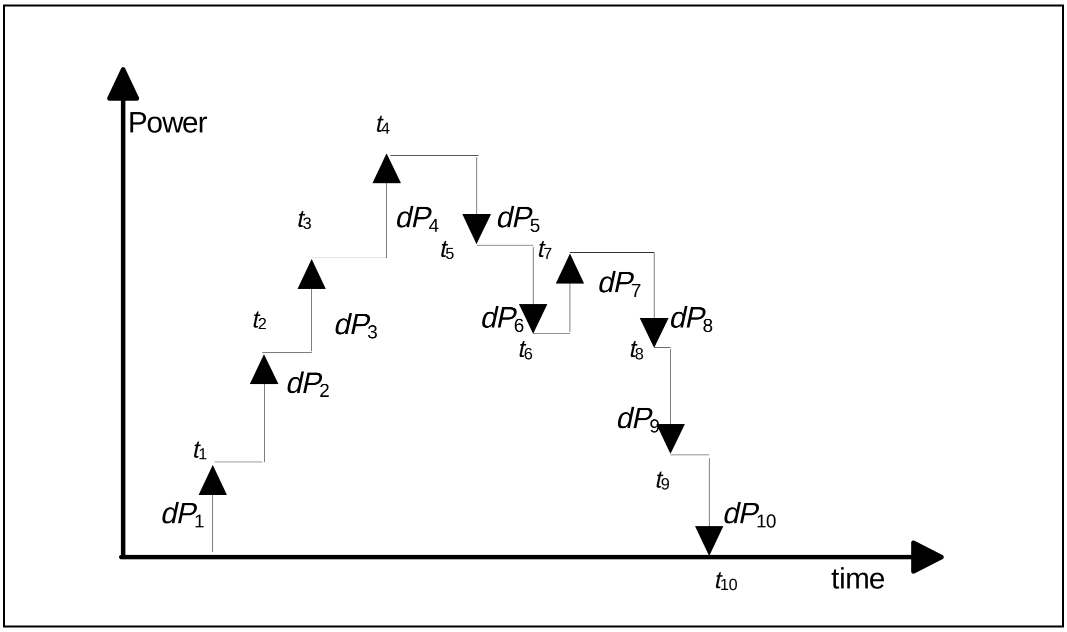

Fig. 18. An example of switching cycles of small appliances.

5 FIELD TESTING RESULTS

5.1 FIELD TESTING SITE

The main field test was performed in a large, single family detached house located in Helsinki. The house consisted of three floors and the total floor area was 275 m^2. The appliance mixture in the house is very extensive and besides this the house is heated with an accumulating electrical heating system. This electrical heating load is much larger than other loads which makes this site very challenging to NIALM.

Table 3 lists the main appliances and also some signatures of appliances in the test house. The water-boiler and water-pump are 3-phase loads. All other are single-phase loads. Also the range has a single-phase supply which is not common in houses with 3-phase supply. In the identification process the range was determined to be a 3-phase load in order to make this arrangement more generally valid. There are about 40 different lights in this house. Half of them are typical 60 W incandescent bulbs. Twelve lights have fluorescent bulbs or a combination of incandescent and fluorescent bulbs. The rest are lights with incandescent bulbs with a power consumption of more than 60 W. The number of television sets is two (88 W and 50 W). The water circulating pump (70 W) of the heating system is operating all the time. Also the compressor motor (190 W) of the old freezer is always on without cycles and therefore cannot be detected non-intrusively.

Data recording began in the beginning of 1995 with a modified MXPQ meter. Later this meter was replaced with the first prototype version of MXPQL meter. From the beginning of May 1997 a standard MXPQL meter was installed in this site. The power threshold was set to 50 W. All power steps above this threshold were recorded and saved into the file with time marks. The number of detected events varied from 300 to 500 per day depending on what appliances were used during a specific day.

Table 3. Main appliances in the test house.

Appliance	Power signature	
	d*P*/W	d*Q*/VAr
Underground floor:		
Water pump (3-phase load)	1290	1189
Water boiler, power 1/3 (3-phase)	10140	0
Water boiler, power 2/3 (3-phase)	19790	0
Water boiler, power 1/1 (3-phase)	29930	0
Refrigerator1	122	106
Freezer	194	274
Water circ. pump (3-phase, always on)	70	167
Clothes washer (many different states)		
Kitchen:		
Refrigerator2	167	178
Refrigerator3	124	127
Coffee maker1	952	-13
Coffee maker2	500	-7
Coffee maker3	753	-10
Microwave oven	1550	110
Toaster	1295	-20
Dish washer (many different states)		
Bread machine (many different states)		
Range (multi-state appliance)		
Special lights:		
Garage light 4x40W	204	373
Kitchen light 120W+40W	170	80
Window light	110	160
Miscellaneous:		
Vacuum cleaner1	880	230
Vacuum cleaner2	780	240
Electric heater	775	-10
Car block heater	600	-10
Car inside heater 800 W	885	40
Car inside heater 1200 W	1185	40

5.2 TOTAL ELECTRICITY CONSUMPTION

Total electricity consumption of the test house during November 1996 is shown in Figs. 19 and 20. It is dominated by the consumption of the hot water boiler (volume 5 m^3) because it is used for accumulating electrical heating. The peak demand of this hot water boiler is about 30 kW. It is controlled (on) in two steps (10 kW + 20 kW = 30 kW) by the utility after 9 p.m. and locally by a thermostat (30 kW on and off). From Monday to Friday the water boiler is allowed to switch on between 9 p.m. and 7 a.m. (Fig. 19). During weekends it can switch on between 9 p.m. and 10 a.m. (Fig. 20).

Electricity consumption is larger during weekends than working days. The inhabitants of the house are usually present during weekends and use electrical appliances for cooking, washing, pumping water, watching TV, etc. more than working days.

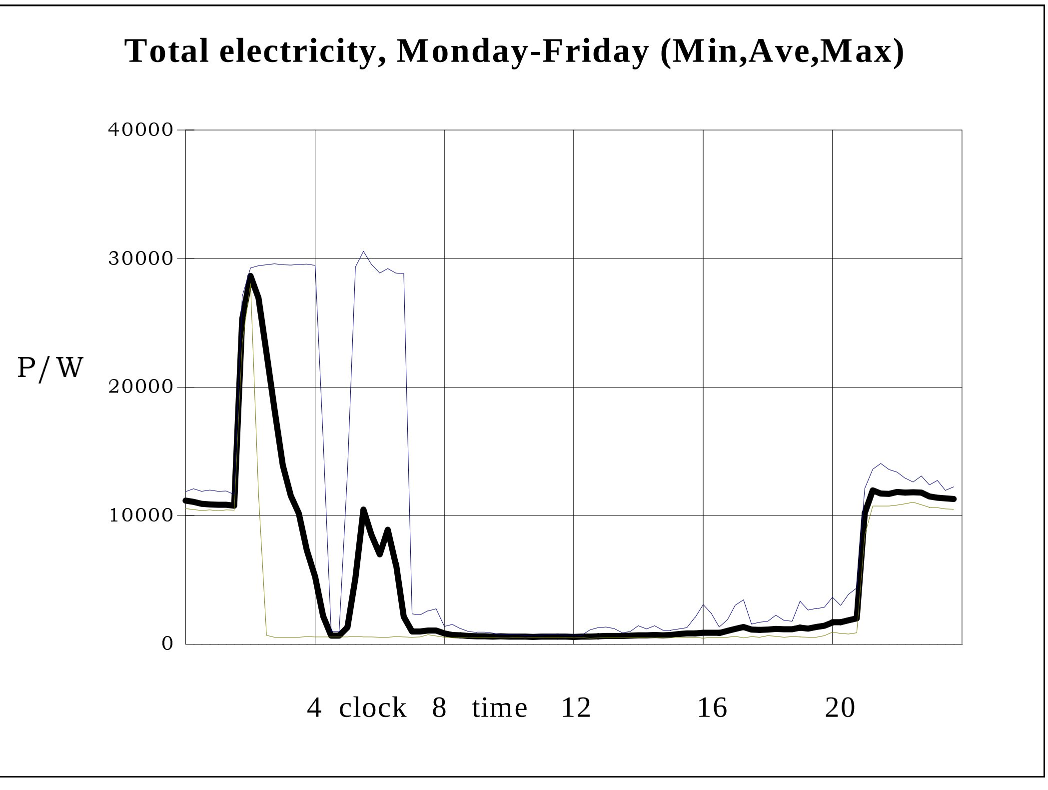

Fig. 19. Average (thick line), minimum (dotted line) and maximum load (thin line) curves (P_{15min}) from Monday to Friday during November 1996.

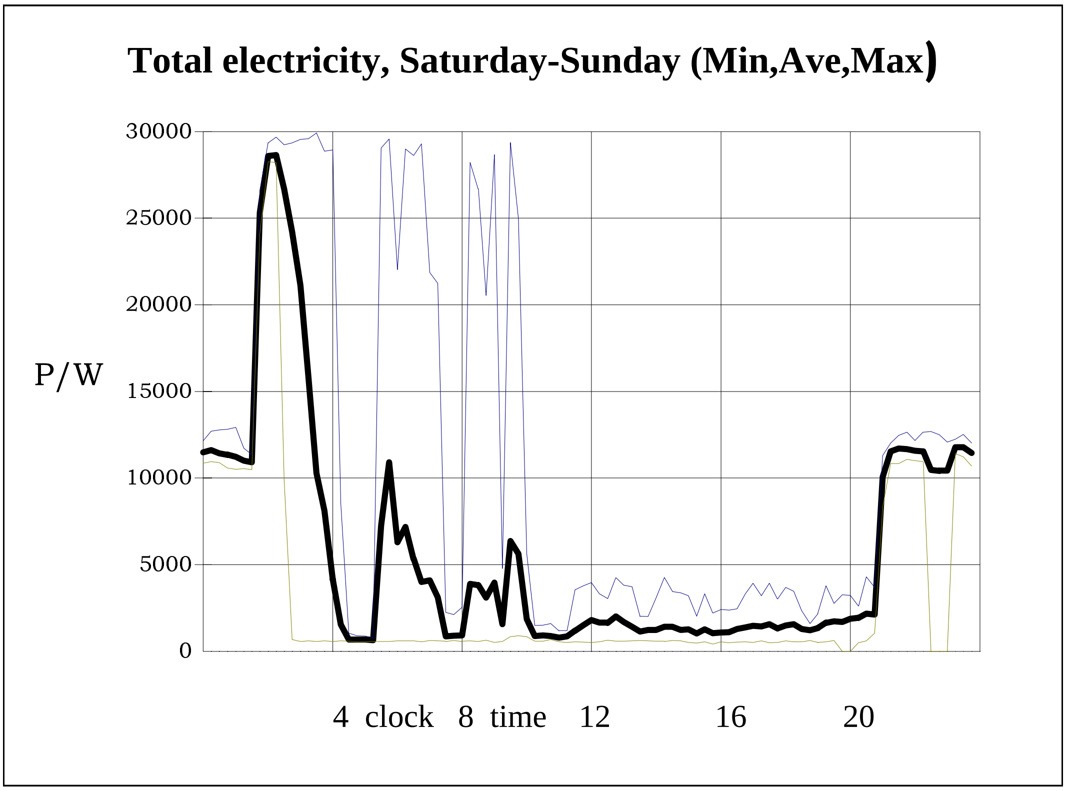

Fig. 20. Average (thick line), minimum (dotted line) and maximum load (thin line) curves (P_{15min}) from Saturday to Sunday during November 1996.

5.3 VERIFICATION OF RESULTS

One essential task is to validate NIALMS data against parallel metered appliances. This also makes it possible to compare the accuracy of NIALMS developed in different countries.

5.3.1 Parallel instrumentation

In order to verify results of the non-intrusive system parallel instrumentation was needed. For this purpose a portable briefcase metering system was developed and it was also possible to borrow some data logger units from the Electricity Association in London in cooperation with the EDEVE-group (see chapter 1.2).

The portable briefcase metering system consists of the Mittrix-meter, current transformers, 1/3-phase switch, power connectors to a three-phase electricity supply through fuses, a connector to a single-phase appliance with plug and an RS-232 serial connector to a PC. This briefcase can be used to monitor either load data at one second intervals or events, either a three-phase supply up to 50 A/phase or an appliance with a plug up to 12 A. This briefcase when it was connected to one appliance at a time made it possible in our test house to simultaneously record events both from total load and from this specific appliance. By transferring the briefcase from one appliance to another it was possible to monitor how appliances behave and get measurements in order to verify results of non-intrusive algorithms.

A data logger system manufactured by Normalair-Garret Limited from England was used to record appliances individually. This system consists of enhanced housing units, data logger units and a down-loader unit. Enhanced housing units are compact enclosures that contain one or more solid-state, current transformer operated, single-phase electricity kWh-meter and provides an unobtrusive housing for the data logger unit which features two independent input channels for recording pulse inputs at user definable periods. Recorded data is retrieved by removing the data logger unit from the enhanced housing unit at the monitoring point and by downloading the data using a down-loader unit and a special software operating on a personal computer. This software constructs an output file which may be displayed on screen or transferred to other programs for data analysis.

5.3.2 Definition of error criterion

Statistics for performance evaluation of the non-intrusive prototype must be chosen according to the final goals. It is difficult to give a quantitative evaluation of errors made while finding or naming appliances. For a given appliance a good criterion would be a classical percentage of errors:

$$\text{criterion1} = 100/n(\text{days}) \cdot \sum_{i=1}^{n(\text{days})} \left| E_{\text{est}(i)} - E_{\text{true}(i)} \right| / E_{\text{true}(i)} \qquad (24)$$

where

n(days) = number of recorded days

$E_{\text{est}(i)}$ = non-intrusively estimated electricity consumption (Wh) of a given appliance during day i

$E_{\text{true}(i)}$ = exact measurement of electricity consumption (Wh) of a given appliance during day i.

Criterion1 describes the accuracy of estimating day energy consumption during the recording period. Another useful criterion would also be a slightly modified version of criterion (24). Criterion (25) describes the accuracy of estimating the energy consumption over the whole recording period as follows:

$$\text{criterion2} = 100/n(\text{days}) \cdot \sum_{i=1}^{n(\text{days})} (E_{\text{est}(i)} - E_{\text{true}(i)}) / E_{\text{true}(i)} \qquad (25)$$

5.3.3 Hot water boiler

The water boiler is the largest load at this site as explained in chapter 5.2. It consumes about 80...90 % from the total electricity use during winter time. The on and off-switching of this multi-state load causes 3...10 events per day (Fig. 21). These symmetrical 3-phase events are much bigger than others and therefore they can be identified practically every time. Fig. 22 gives the results of non-intrusive estimation and parallel measurements. The measured data shows the exact value. The average error of the non-intrusive method identifying this load in daily consumption during the 9^{th}...14^{th} of April 1996 was 1.3 % according to criterion (24) and -1.3 % according to criterion (25). This small systematic error means that all events during the dates of Fig. 21 have been identified and the reason for this small error is the noise in recording the events.

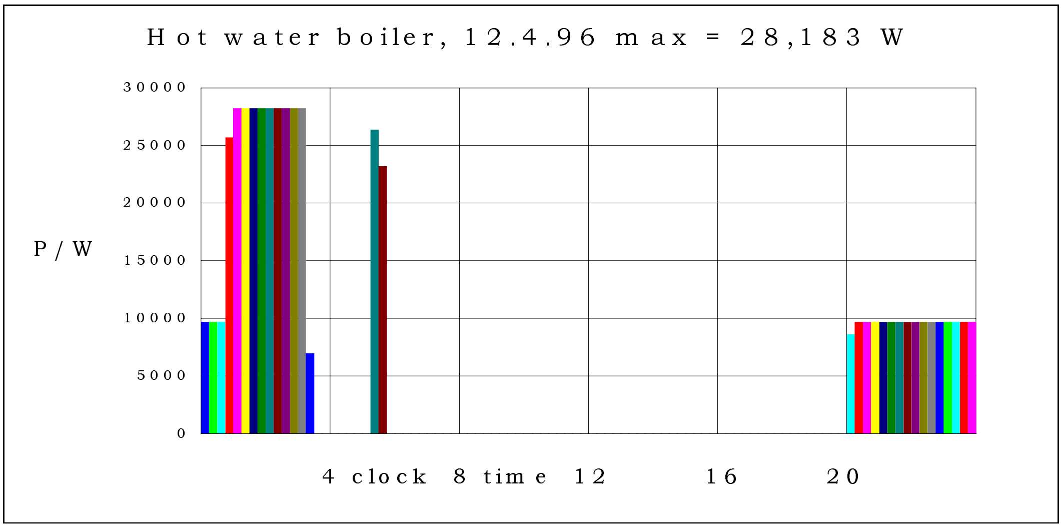

Fig. 21. Typical one day load curve of the hot water boiler (one pillar means 15 minutes average power).

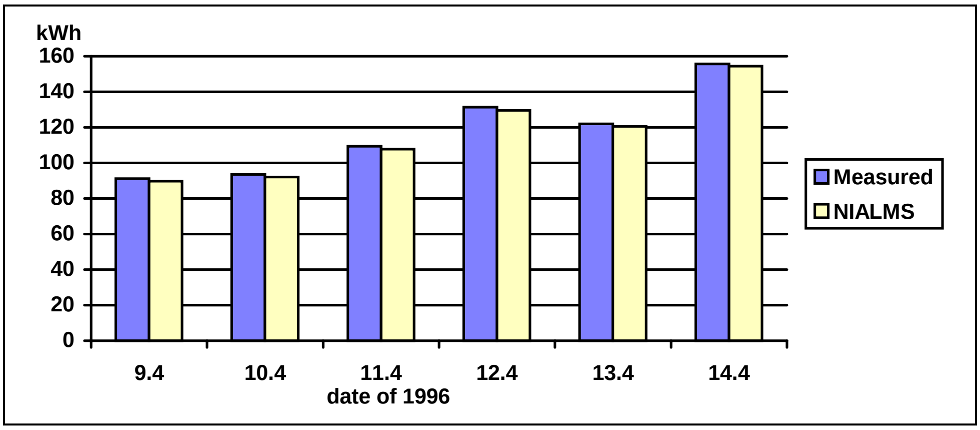

Fig. 22. Daily energy comparison of water boiler load (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.4 Water pump

Another 3-phase load is the water pump which is operated by an electric motor (on/off-load). The motor consumes 1300 W during pumping. The number of on and off-switchings or events of this pump per day varies from 10 to 30 depending on how much water is used in a specific day. Typical on-cycle time of the pump is about one minute, but if water is needed in abundance the on-time increases respectively. Fig. 23 shows an example of a typical load curve of the water pump during a specific day. Fig. 24 shows the results of non-intrusive estimation and parallel measurements. The measured data shows the exact value. The average error of the non-intrusive method identifying this load in daily consumption during the 4th...7th of May 1996 was 7.4 % according to criterion (24) and -5 % according to criterion (25). This error means that some events are missed because of simultaneous events. If the algorithm can't recognize either an on or off-event one on-cycle is missed.

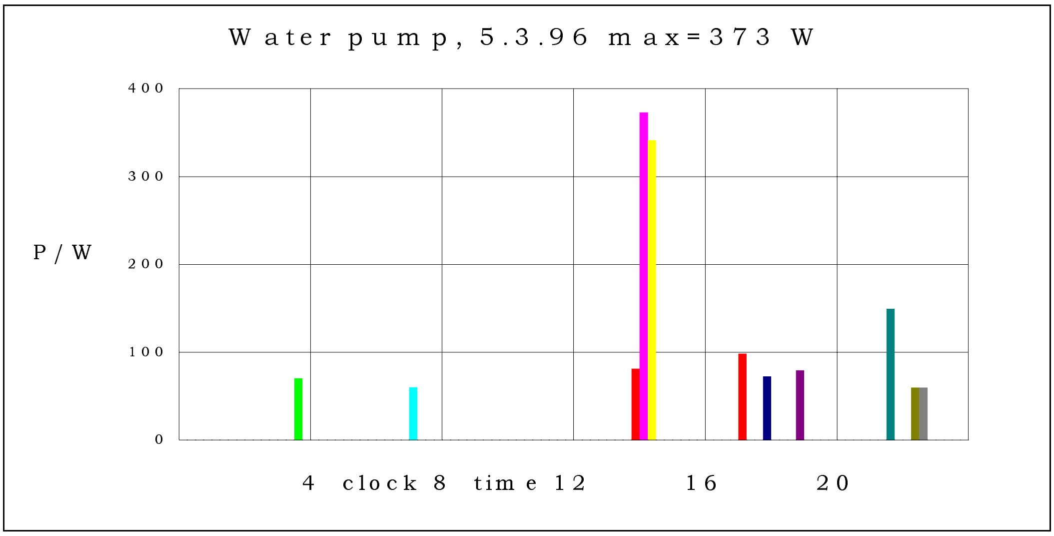

Fig. 23. Typical one day load curve of water pump (one pillar means 15 minutes average power).

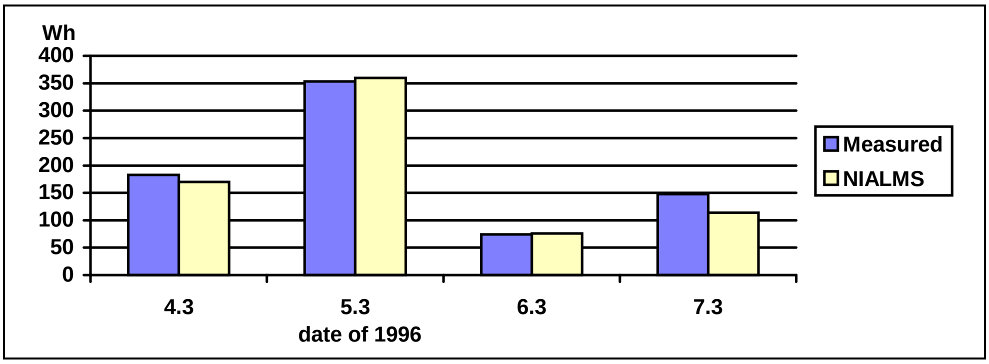

Fig. 24. Daily energy comparison of water pump (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.5 Electric range

A range represents a very complicated multi-state appliance (see Table 2). Its signatures overlap with the ones of many other appliances. Therefore every time the algorithm finds an event possibly belonging to the range, overlapping analysis (described in Fig. 15) must also be performed. The large possibility to misinterpret this kind of event reduces the estimation accuracy. Fig. 25 shows a typical day load curve of the range during the weekend. The main use of the range appears to be at midday which apparently is the most common cooking time. Fig. 26 shows the differences of day consumption in measured and non-intrusively estimated values between the 16th and 31th of May 1996. The average error according to criterion (24) is 15 % and 8.3 % according to criterion (25).

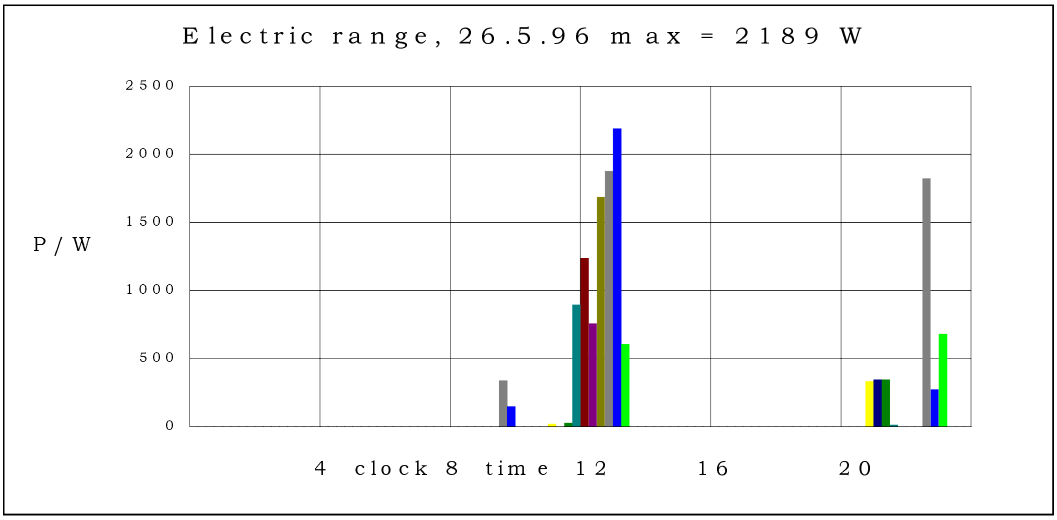

Fig. 25. Typical one day load curve of the electric range (one pillar means 15 minutes average power).

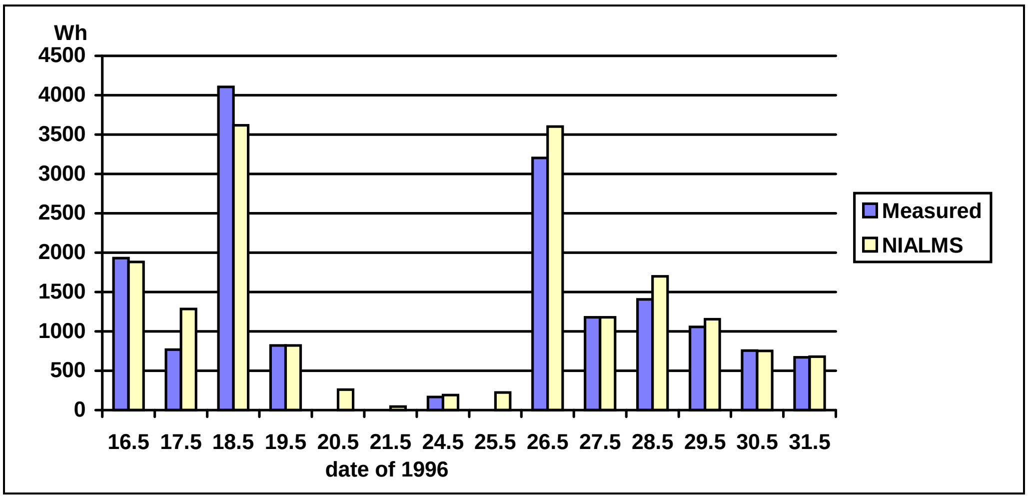

Fig. 26. Daily energy comparison of the electric range (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.6 Coffee maker

According to Table 3 there are three coffee makers in the house. Only the most frequently used one was verified with parallel measurement. Its nominal power is 950 W. Typically this coffee maker is in use three times per day (Fig. 27). One operation period in Fig. 27 consists of boiling and warming cycles. The boiling cycle includes one on and off-event and takes about five minutes. The warming cycle respectively has many on and off-events because it is controlled thermostatically and its duration time depends on how long the coffee maker is switched on. Fig. 28 shows the differences of daily consumption in measured and non-intrusively estimated values between the 29th of May and 9th of June 1996. The average error according to criterion (24) is 6.1 % and 0.4 % according to criterion (25).

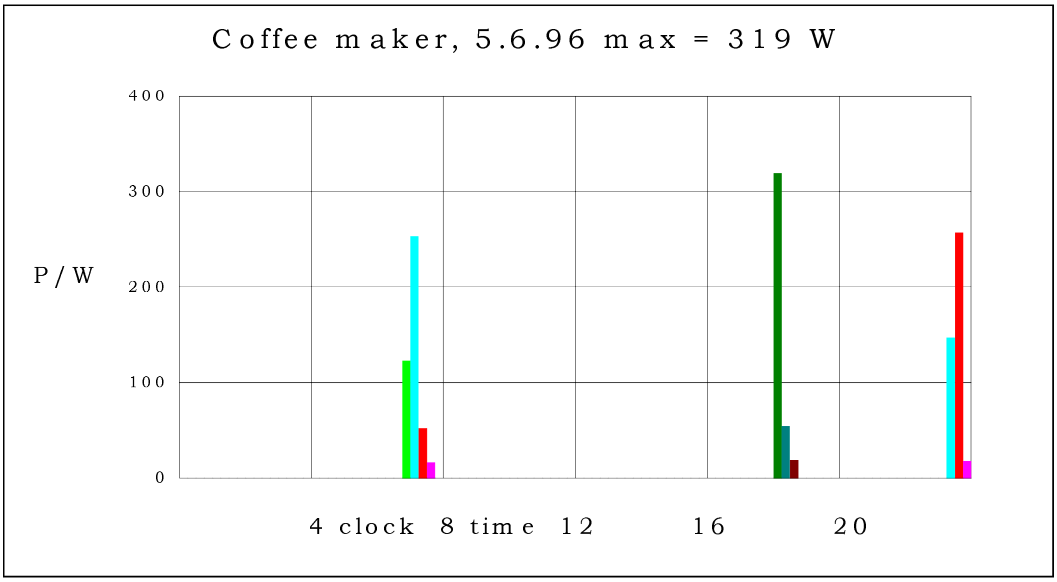

Fig. 27. Typical one day load curve of the coffee maker (one pillar means 15 minutes average power).

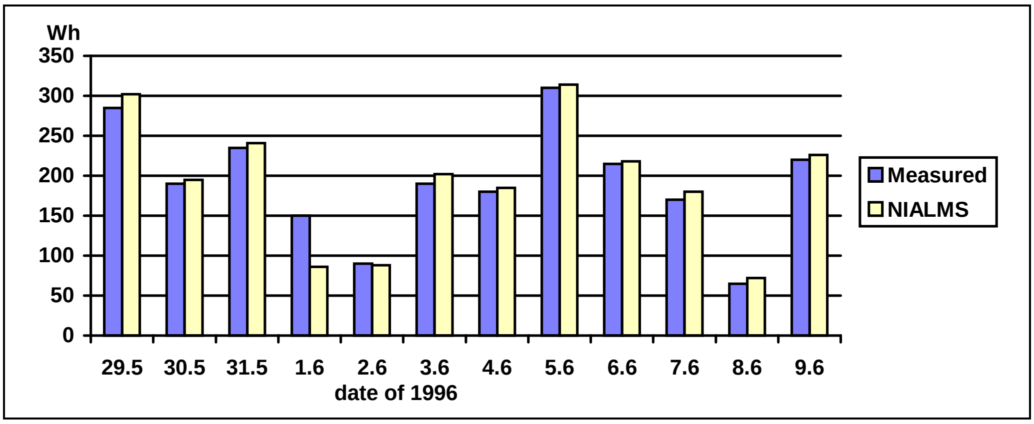

Fig. 28. Daily energy comparison of coffee maker (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.7 Microwave oven

The microwave oven is typically used irregularly for short times (Fig. 29). One short period operation includes many on and off-events. One on-cycle can take only a few seconds. The signature of the microwave oven (in this case 1550 W, 110 VAr) has a small reactive component which is useful in order to separate it from the range. Fig. 30 shows the differences of daily consumption in measured and non-intrusively estimated values between the 3rd and 10th of November 1996. The average error according to criterion (24) is 11.1 % and 3.6 % according to criterion (25).

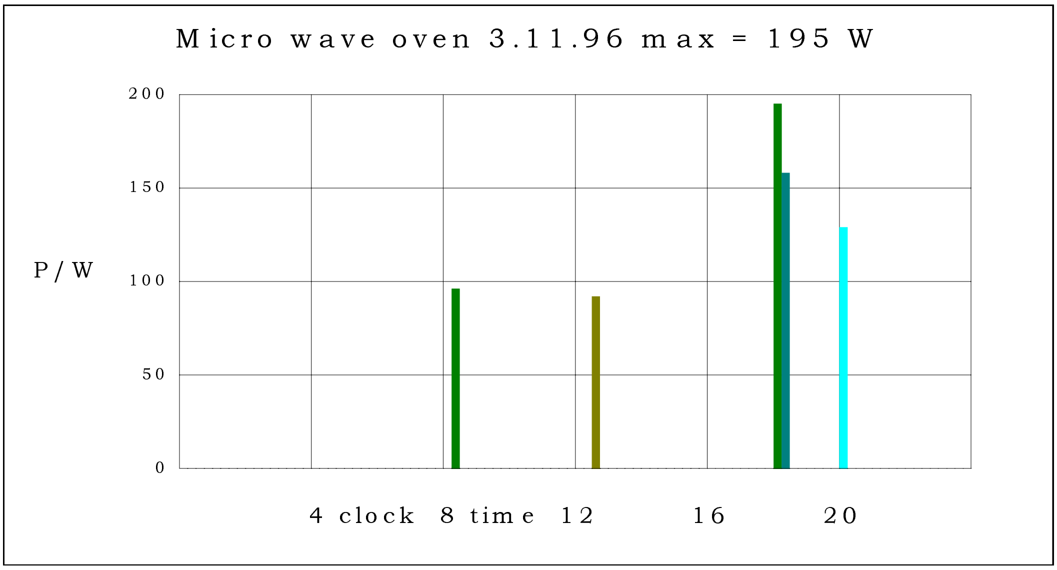

Fig. 29. Typical one day load curve of the microwave oven (one pillar means 15 minutes average power).

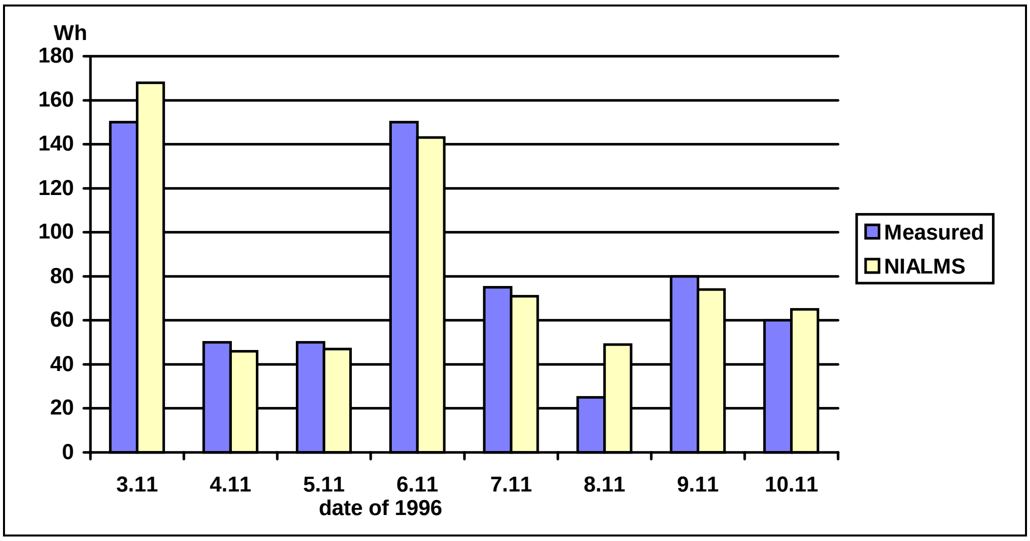

Fig. 30. Daily energy comparison of microwave oven (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.8 Dishwasher

Dishwashers normally have a water heating resistor and a motor for pumping water. The power rate of the resistor in this case is 1940 W. The signature of the pumping motor is very unusual when compared to other domestic appliances. The on-signature (90 W, -170 VAr) is in quadrant IV which means that the motor is overcompensated with a capacitor. The off-signature (-210 W, 170 Var) is in quadrant II and during pumping the active power consumption of the motor increases from 90 W to 210 W. This is the consequence of an increasing load on the pump as the water level rises during a filling cycle. A typical washing period consists of heating, pumping and washing cycles (Fig. 31). Most energy is consumed during water heating if the washer has a cold water connection.

Fig. 32 shows the differences of daily consumption in measured and non-intrusively estimated values between the 29[rh] of October and 10[th] of November 1996. The average error according to criterion (24) is 33 % and -33 % according to criterion (25).

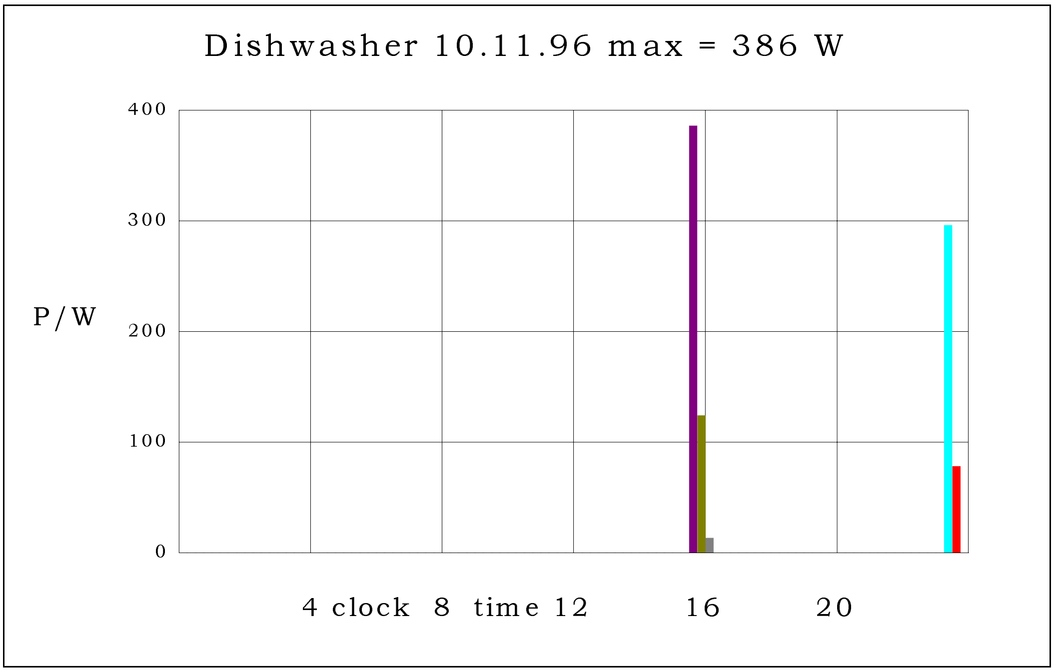

Fig. 31. Typical one day load curve of the dishwasher (one pillar means 15 minutes average power).

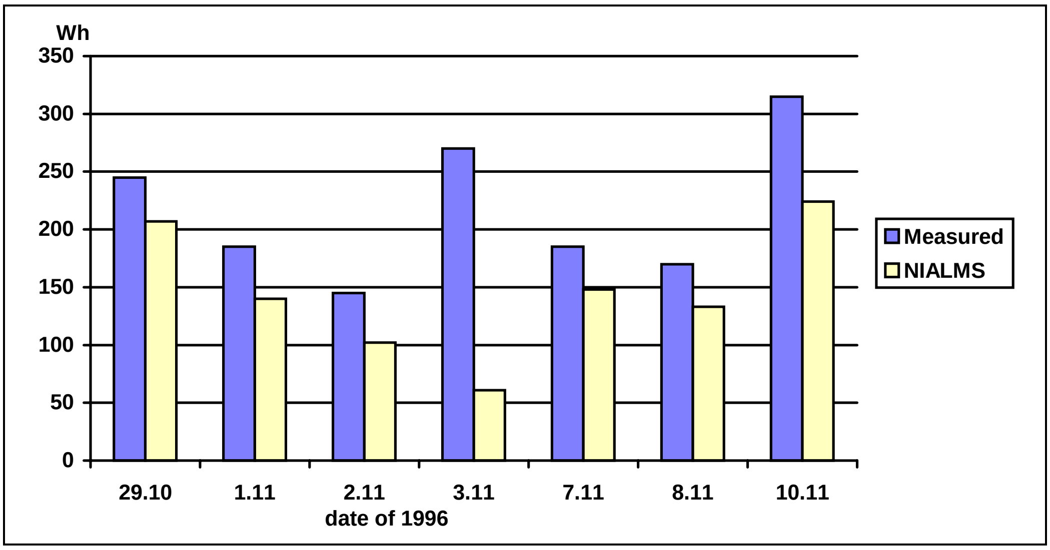

Fig. 32. Daily energy comparison of dishwasher (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.9 Clothes washer

The clothes washer has a water heating resistor and two motors; one for pumping water and the other for rotating the drum. The last one has a very specific signature in this case (see Fig. 11 on page 32). It is caused by cyclic reversals of the drum during rotation. The events are distributed along a line in quadrants I and III because the motor is controlled by a semiconductor unit. Because the heating element and the drum motor can often switch simultaneously and the power of the drum motor varies over a large range the identification is based on special models described in Fig. 6. Fig. 33 shows a typical daily load curve including one washing period. It should be noticed that the clothes washer in our test house is one of the most difficult to identify non-intrusively (Rissanen 1998).

Fig. 34 shows the differences of daily consumption in measured and non-intrusively estimated values between the 7^{th} and 30^{th} of September 1996. During the 14^{th} and 24^{th} of October the clothes washer and the range were in use at the same time. In this case the clothes washer and the range are supplied by the same phase (single-phase range). Therefore the error of estimation is large during these days. The average error according to criterion (24) is 24.8 % and -24.8 % according to criterion (25).

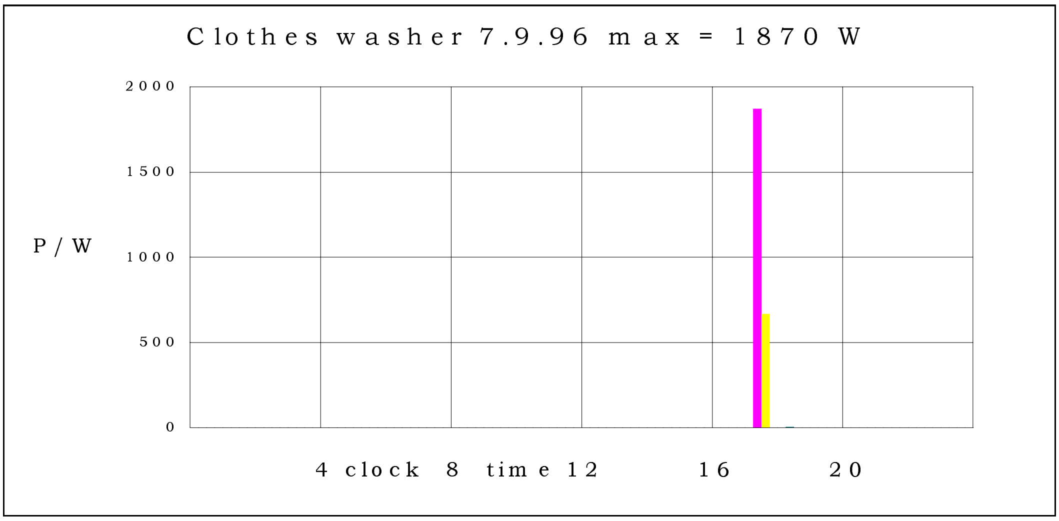

Fig. 33. Typical one day load curve of the clothes washer (one pillar means 15 minutes average power).

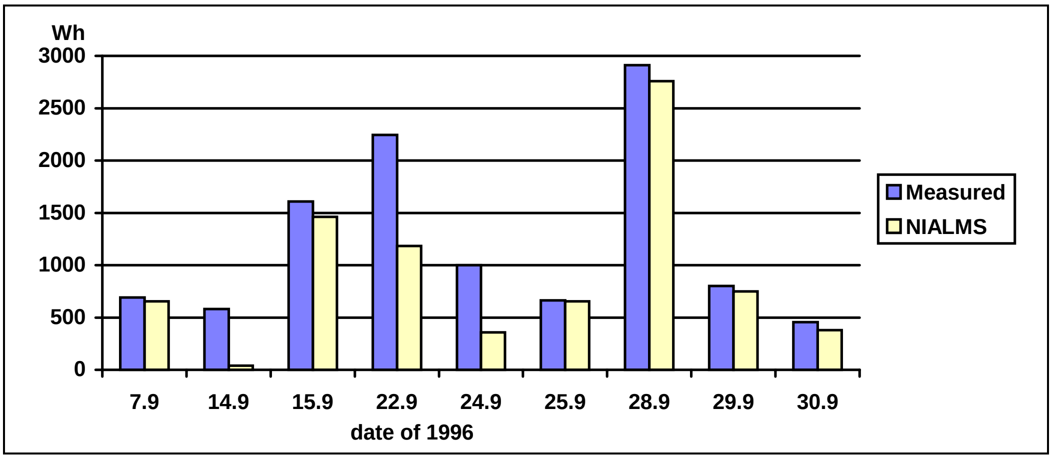

Fig. 34. Daily energy comparison of clothes washer (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.10 Refrigerator

Common appliances existing in almost every household are a refrigerator and freezer. In our test house there were three refrigerators and one freezer. The last one, as mentioned earlier, is running all the time and therefore can't be detected non-intrusively. This is not normal operation and in this case the reason for the abnormal situation might be the 20 year age of the freezer.

The largest and most electricity consuming refrigerator was chosen for parallel measurements. The absolute value of the real power of the on-signature (150 W, 180 VAr) is greater than the one of the off-signature (-130 W, -180 VAr). This is the normal situation in the case of cooling compressors. The refrigerator on and off cycles are controlled by a thermostat. In this case the on-cycle and off-cycle duration are about 25 minutes. A typical daily load curve is presented in Fig. 35. It shows that some operation cycles are missed during night time between 1 a.m. and 3 a.m. During that time the water heater also operates at its maximum power (10 kW/phase) and therefore the accuracy to detect small events at that time is poor. That's why the estimation accuracy of daily consumption of small power appliances in our test house is better during summer time than winter time (the operating time of the water heater at maximum power is considerably longer in winter than in summer).

Fig. 36 shows the differences of daily consumption in measured and non-intrusively estimated values between the 14[rh] and 21[st] of November 1996. The average error according to criterion (24) is 10.5 % and -10.5 % according to criterion (25). It can be assumed that the error of estimating consumption of cooling machines in common households without big water boilers is much better.

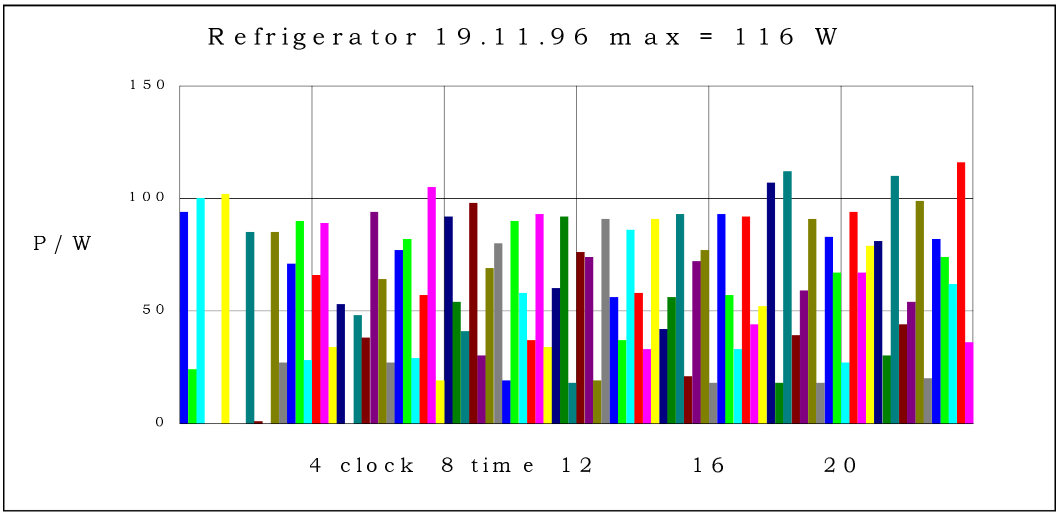

Fig. 35. Typical one day load curve of the refrigerator (one pillar means 15 minutes average power).

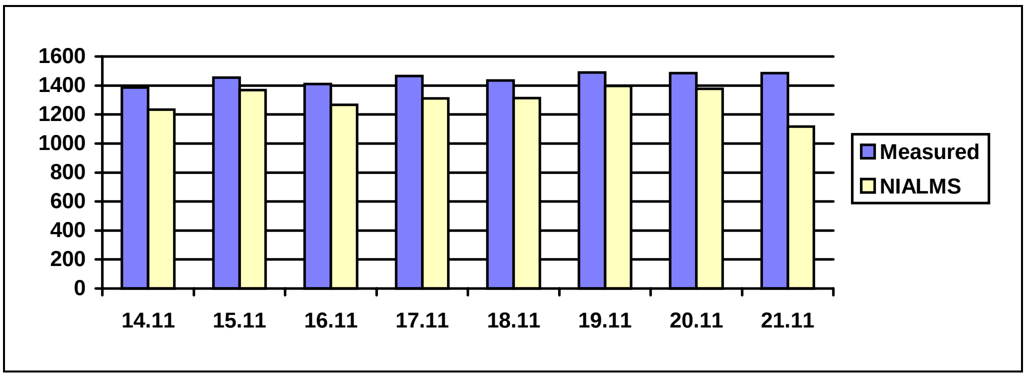

Fig. 36. Daily energy comparison of refrigerator (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.11 Toaster

The toaster is an appliance whose signature (+/- 1300 W, 0 VAr) overlaps with the one of the range. The use of the toaster is quite irregular. Fig. 37 shows the differences of daily consumption in measured and non-intrusively estimated values between the 29[rh] of May and 7[th] of June 1996. The average error according to criterion (24) is 6.6 % and 0.2 % according to criterion (25).

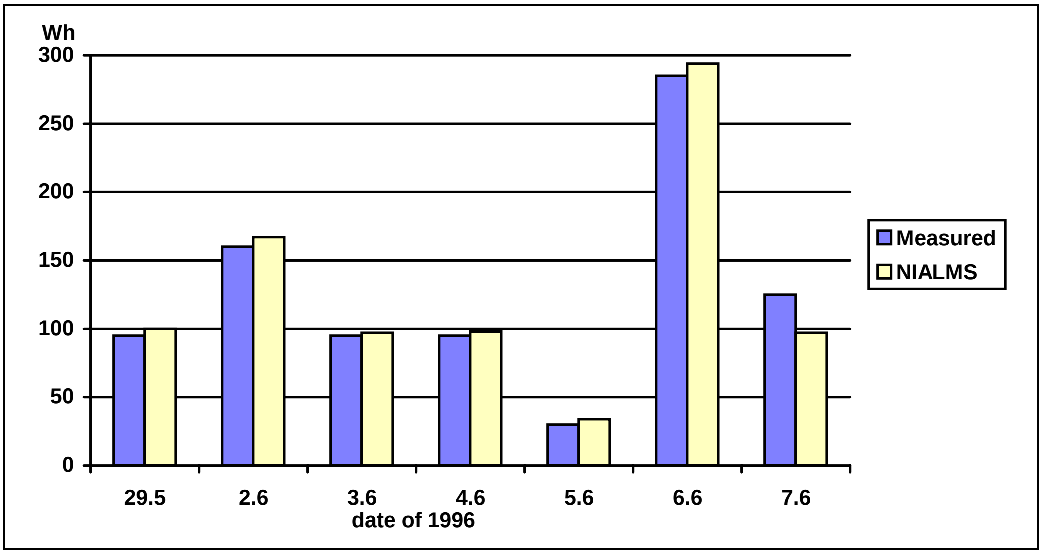

Fig. 37. Daily energy comparison of a toaster (Measured = exact value, NIALMS = non-intrusively estimated value).

5.3.12 Comparison to other NIALMS

Table 4 summarizes the testing results of the prototype NIALMS developed at VTT Energy in the case of one large household customer. Criterion (24) describes the errors on a daily energy level and criterion (25) gives the energy error over a longer period, like a week or a month.

The values of table 4 can be in principle compared to the results of the other development work in Europe. Table 5 gives the first field results of the Hidden Markov Model algorithms developed at Electricite de France by Marc Bons (Bons & Leonardi 1996). The results of Table 5 should be compared to the results of error criterion (25) in Table 4.

Table 4. Non-intrusive estimation errors of different appliances in one household in Finland.

Appliance	Error criterion (24) (%)	Error criterion (25) (%)
Hot-water boiler	1.3	-1.3
Water pump	7.4	-5
Range	8.3	15
Coffee maker	6.1	0.4
Microwave oven	11.1	3.6
Dishwasher	33	-33
Clothes washer	24.8	-24.8
Refrigerator	10.5	-10.5
Toaster	6.6	0.2
Average	*12.1*	*-6.2*

Table 5. Non-intrusive estimation error over a 2 week monitoring period in two households according to Electricite de France.

Appliance	Setting #2, error (%)	Setting #3, error (%)
Water heater	-6	-
Refrigerator	11	-6,6
Clothes washer	-45	-38
Dish washer	-26	-
Oven	-	-18
Micro wave oven	-	2
Average	*-16.5*	*-15.2*

Wide field testing of NIALMS prior to marketing is underway in the United States. Beta testing includes a parallel metering verification program performed by Plexus Research, Telog Instruments (manufacturing company) and many utilities (Buckeye Power, Consolidated Edison of New York, East Kentucky Power, Entergy Services Company, Potomac Electric Power Company, Public Service Electric & Gas of New Jersey and Southern California Edison). The data in Table 6 is based on preliminary results from this program. This information was available to the EDEVE working group during summer 1996. One interesting point in Table 6 is the seasonal differences in the accuracy of NIALMS. According to the latest information (Carmichael et al. 1997) the latest NIALMS software (Beta v2.44) is able to identify two-state appliances like air conditioners, swimming pool pumps, waterbed heaters and simple frost-free refrigerators with as much as 99% accuracy (threshold = 150 W). Identification of complex multi-state appliances requires additional development. Appliance naming in the latest software version is semi-automatic.

Comparison between developed systems in Europe and in the United States is difficult because of the differences in appliance stock and power supply in households. It should be especially noticed that the results of tables 4, 5 and 6 are based on 3-phase, single phase and two phase power supply NIALMS respectively. Also the number of sites, the size of tested households and duration of monitoring periods are different.

Table 6. NIALMS accuracy based on monthly kWh comparisons according to Plexus Research in the United States (n = number of measured customers, % = accuracy).

Appliance	Summer June-Aug (n , %)	Transition Sept,Oct,Apr, May (n , %)	Winter Nov-Mar (n , %)
Water heater	9 , 95	12 , 97	16 , 95
Well pump	7 , 92	7 , 95	12 , 90
Sewage pump	-	3 , 95	3 , 95
Water bed heater	3 , 93	-	-
Air source heat pump	5 , 92	6 , 65	5 , 65
Ground source heat pump	6 , 90	7 , 80	12 , 65
Refrigerator	4 , 90	9 , 88	20 , 85
Freezer	-	3 , 89	3 , 89
Dryer	-	4 , 78	-
Average	*92.3*	*87.0*	*83.9*

5.4 MONTLY ENERGY CONSUMPTIONS OF APPLIANCES

Non-intrusively estimated electricity consumption of different appliances in our field test house during June 1996 are shown in Appendix 2 and during November 1996 in Appendix 3.

During June total electricity consumption was 2180 kWh. About 70 % (1523 kWh) of this was consumed by the hot water boiler. The remaining 30 % (657 kWh) can be divided into two different main groups: identified appliances (10 %) and other (20 %). The biggest consumers of the identified appliances are small appliances (79.4 kWh), refrigerator 1 (40 kWh), range (35.5 kWh) and fluorescent lights (25.7 kWh). To the last group (other) belong two big consumers: freezer (140 kWh) and the water circulating pump of the heating system (50 kWh). Both appliances operate continuously and therefore can’t be detected non-intrusively. The rest of the consumption in this group (other) belongs to small continuously operating appliances, unidentified appliances and residual energy which contains the error energy of non-intrusive underestimation (see Table 4 criterion (25)).

During November total electricity consumption was 3808 kWh. About 80 % (3034 kWh) of this was consumed by the hot water boiler. The rest of the consumption is divided mainly among small appliances (108.6 kWh), fluorescent lights (45 kWh), range (47 kWh), refrigerator 1 (39 kWh) and other (476.6 kWh).

The consumption of small appliances and fluorescent lamps has increased compared to the values of June because the need for lighting is greater during November. Figs. 38 and 39 show the average load curves of small appliances during both months. These results has not been verified by parallel measurements. Generally it was checked with the residents of the test house that these results are reasonable.

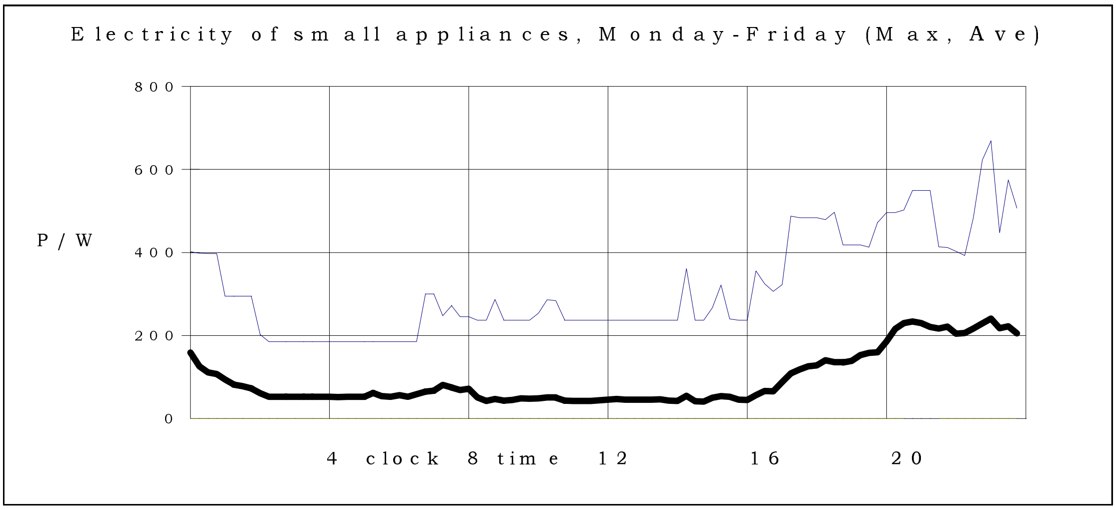

Fig. 38. Average (thick line), maximum load (thin line) curves of small appliances from Monday to Friday during June 1996.

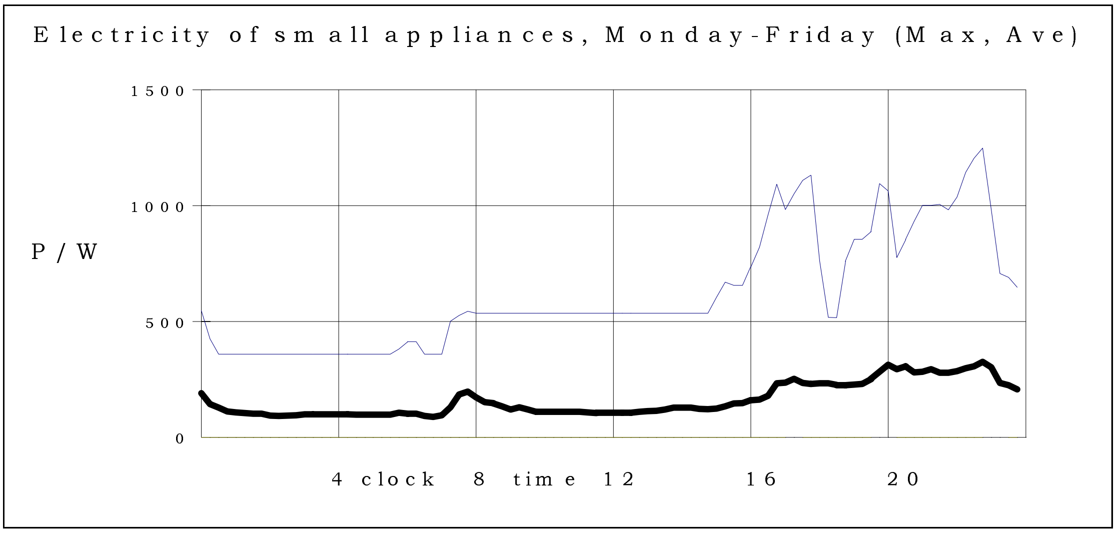

Fig. 39. Average (thick line), maximum load (thin line) curves of small appliances from Monday to Friday during November 1996.

5.5 EXPERIENCES IN NON-DOMESTIC FIELD TESTING SITES

Also some non-intrusive measurements were performed in non-domestic buildings. These recordings were done in connection with a large project of IVO Technology Centre. The purpose of the IVO project was, together with utilities, to collect and analyze energy use data in one hundred commercial buildings. Especially the distribution of electricity (lighting, heating, ventilation and other) inside buildings was under consideration. Most of the buildings were electrically heated. In some buildings IVO installed instrumentation in order to separate different consumption groups as accurately as possible. Some of these buildings having better instrumentation were chosen as test sites for NIALMS. These tests were short term and the purpose was to consider the applicability of this system for this type of customers.

The first site was a commercial building in which cars were sold and repaired. The total floor area was 1600 m^2. The size of main electrical supply was 3x250 A (173 kW). The biggest load was electrical heating which consisted of the following parts: infrared reflectors 101 kW, electric radiators in rooms 6.4 kW, heating in air inlet unit 1 35 kW (13 power steps, each 2.7 kW) and in unit 2 13 kW (10 power steps, each 1.3 kW). Other big loads were the hot water boiler (6 kW), air compressor (7.5 kW), indoor lighting 14 kW and outdoor lighting 4.5 kW. In the repair hall many different electric tools were used. The event recorder was installed in the main supply board. The installed meter was a modified MXPQ(0.5)-meter (accuracy class 0.5). This meter measures only total reactive power and therefore fundamental reactive power was not available. On/off-switching experiments were done during evening when normal action in the building was finished. The on and off-power of all main appliances could be identified when they were manually switched on and off separately. The normal recording was done at the end of May during two days and therefore electrical heating was practically not in use. The average active power per phase was about 10 kW and reactive power 9 kW during daytime. At these power levels the meter was capable of detecting all necessary events and during daytime the number of events per hour varied from 70 to 280 when the threshold of the smallest detected power step was 150 W.

The second site was a day-care center for children. Measurements were done with a modified MXPQ(0.5)-meter in two separate electricity subboards, one supplies kitchen appliances and the other HVAC and food cooling appliances. Most appliances in this kind of kitchen are highly resistive and the reactive power is small. This makes the detection of events of appliances having a small reactive power component difficult. In this site our NIALMS revealed that the cooling compressors of the refrigeration units were cycling on and off unusually often (20 sec. on, 30 sec. off). Long time operation of this kind of cycling would lead to early failure of motors and therefore the maintenance personnel of the building were informed of this abnormal situation.

The third test site was also a day-care center for children similar to the previous one. In this site the purpose was to test the new power quality MXPQL(1.0)-meter (accuracy class 1.0) and to install meters both in the main electricity board and in one sub-board. MXPQL also measures fundamental reactive power. The sampling of the MXPQL is different from the MXPQ. Tests at this site revealed that this meter was not as suitable as the MXPQ for non-intrusive monitoring of non-domestic customers. After these tests the standard MXPQL-meter was installed in our test house and the results were as good as with the prototype meter.

The fourth testing site was a shopping center. The meter, type MXPQ(1.0), was installed in the electricity sub-board which supplies HVAC-machines, outdoor lights and lights in corridors and three lifts. The instant apparent power per phase during daytime was about 46 kVA (P = 35 kW and Q_{tot} = 30 kVA). The number of events per day varied between 500...600 (minimum detected change 400 W) of which about 90 % belonged to the operation of lifts. The loading of lifts was difficult to monitor non-intrusively because of variable loads. Other loads could be detected normally but not during the time when the lifts were in continuous use.

5.6 SUITABILITY OF MITTRIX-METER TYPES FOR NIALMS FOR DIFFERENT CUSTOMERS

According to the field testing experience so far, it is possible to say what type of Mittrix-meters can be used for non-intrusive monitoring at different customers sites. Table 7 summarizes these results.

It should be noticed that the values for maximum apparent power S in Table 7 are only guidelines. The minimum detected power threshold should also be increased according to the maximum measured nominal power. In households, a realistic threshold is 50 W.

Some appliances, especially in the case of non-domestic customers, can be very difficult to detect non-intrusively and when in operation they can make the detection of more simple appliances more difficult. The same problem exists in the case of a customer who has many electrical heaters with electronic control which repeatedly execute very short on-cycles.

Table 7. KWh-meter types of Mittrix used in NIALMS-prototype.

MITTRIX-METER TYPE (ACCURACY %)	QUANTITIES USED IN NIALMS	CUSTOMER TYPE	REMARKS
MXPQL (1.0)	U , P , Q_{1f}	Domestic or non-domestic S<10 kVA/phase	No electrical heaters with electronic control
MXPQ (0.5)	U , P , Q_{tot}	Non-domestic S<100 kVA/phase	Phase angle of all phase total loads > 6°
MXPQ (1.0)	U , P , Q_{tot}	Non-domestic S<50 kVA/phase	Phase angle of all phase total loads > 6°

MXPQ-meters can’t be used in households because they are not able to measure total reactive power at small phase angles (< 6°). The phase angle in households is small compared to non-domestic customers which have three-phase motors and fluorescent lighting, often operating during night-time also. If a non-domestic customer has a centralized compensation capacitor then phase angle is small and the meter type MXPQL is the only possibility for non-intrusive monitoring.

6 DEVELOPMENT OF THE APPLICATIONS

In this chapter the possibilities to use NIALMS in different applications will be discussed. Knowledge of electricity consumption and time of use in individual buildings is vital to consumers and electric utilities. The information, typically provided by a billing kWh-meter at the point of electrical service to a building is the basis for billing and payments. In the case of households and other small consumers billing meters are only able to register energy in kWh in one or two different registers (day and night energy separated). Bigger consumers have billing meters with a time scale on the order of 15-60 min and also registers for peak loads. This improves the temporal resolution beyond that afforded by daily or monthly totals of electricity usage and provides some information about the scheduling of electricity-consuming appliances. The multipurpose kWh-meter presented in this study drastically changes this situation, especially in the case of small consumers. The same meter for a moderate investment can be used for billing, power quality monitoring and appliance end-use monitoring.

6.1 LOAD RESEARCH

With the purpose of improving the knowledge of the structure of electricity consumption, the current development and the possibility of influencing consumption, many utilities all over the world have launched load research programs covering customers from residential to industrial. Load research is based on load data which usually can be obtained by special metering instruments and manual labor when the metering equipment is installed at the customer's site. In Finland load research started in the year 1983 and forty utilities participated in it. In that project 60 min. load recordings were monitored from 1000 customers' total loads. No individual appliance load recordings were done. This topic is treated in reference (Seppälä 1996).

In some countries like the United States, the United Kingdom and France appliance load recordings in residences have been performed with special intrusive equipment. Large utilities typically monitor dozens to hundreds of their residential customers with intrusive load monitors placed on two to eight major loads. In this application NIALMS is especially useful for utility monitoring of residential loads because it will allow more appliances to be monitored in more homes. The easy installation and low cost of NIALMS are very valuable features from the utility's perspective.

The prototype NIALMS described in this report could be further developed in order to apply it in load research data collection. Product development needs to combine a power quality kWh-meter and event recording software in order to get rid of the laptop PC at the monitoring site. This event meter should be remotely readable e.g. telephone lines and have enough data storage capacity. This event data would be transferred to a master station where load identification would be performed. If appliances are named automatically then a large database of power levels and duration of cycles from different appliances should be available. The work of collecting this kind of data from household appliances of different manufacturers is going on at VTT Energy and is presented in the Master's thesis work of Juha-Pekka Rissanen (Rissanen 1998).

6.2 DSM-APPLICATIONS

One potential application for NIALMS is the evaluation of demand side management (DSM) programs (Pihala & Kärkkäinen 1996). End-use metering, if carried out before and after the DSM program implementation, can provide estimates on energy and demand savings as well as end-use load profiles. This data can be used to correct the implementation of ongoing programs and to improve the design and implementation of future programs. Similar information can also be utilized in the operation of direct load control. Many electric utilities install appliance controllers on certain loads throughout their customer base, to shed them during times of peak power usage. This operation can be even more effective if NIALMS can monitor these loads in almost real-time in order to verify that the shedding system is in fact operational.

The cost of end-use metering has been the major barrier to its larger use. Also the time span required to collect the data may be long, ranging from a few months to a year. These barriers may be overcome with the NIALMS based on the multipurpose kWh-meter presented in this study. Because the same meter can be used for several purposes there is no need to install new measurement equipment for DSM programs.

Some energy-conscious individuals would be very interested in detailed data for their own energy consumption if it were conveniently and inexpensively available. The NIALMS could be installed temporarily at the resident's request. This would result in detailed data of how electricity is used in a residence, increasing the relationship between the customer and the utility by producing new services such as a detailed billing per use or measures of how to make electricity use more effective.

6.3 FAILURE ANALYSIS AND SECURITY APPLICATIONS

One interesting use for this technology is to locate and identify device failures which might be evidenced by unusual power consumption or duty cycle characteristics. In this application the meter is used as a smart sensor which possibly could simultaneously replace many other sensors used for surveillance in buildings, like a temperature sensor in the sauna or in a refrigeration room or sensors in HVAC-machines. Of course a special software should be developed for this application. For example in our test house NIALMS revealed two types of equipment faults or abnormal operation modes. First it was observed that the freezer had no on/off-cycles but it was always in the on-state at maximum power consuming lots of electricity. Secondly, during winter time the block heater of a car was switched on but NIALMS didn't get any signs of this operation and it was observed that the connection between the cable and the heating element near the motor block was loose.

In commercial buildings the NIALMS can be a part of a building automation system. When the automation system controls e.g. major HVAC equipment on and off the NIALMS can give feedback if the motors don't operate at normal power level. This way NIALMS can support a building automation system and because we have access to important information, namely the identity of a device and the precise time at which the control system initiates a start-up or shut-down signal, the identification and naming of appliances is easy. Examples of some field tests of this kind of application can be found from references (Nordford et al. 1992) and (Nordford & Leeb 1996).

As a security example, a vacation home which is unoccupied for long periods can be monitored at a single point. The monitor could be programmed to automatically generate a phone call to report appliance usage above or below a specified threshold. If the refrigerator or freezer fails, if lights are turned on, if the water pump operates excessively (perhaps indicating a burst pipe), etc., the owner would be notified immediately. Home automation is a closely related application area. Unfortunately, these applications also suggest issues of privacy, and surveillance applications in which the NIALMS can be abused. These topics are treated in reference (Hart 1989).

7 CONCLUSIONS

The non-intrusive electric appliance load monitoring system (NIALMS) provides information about the operation of major electrical equipment by sampling electric power at a single point without sub-meters. The most attractive features of this system are ease of installation, low cost and monitoring without disturbing customers. Traditional load monitoring requires complex hardware and simple software, while NIALMS reverses that balance. In the unique NIALMS-prototype presented in this study a 3-phase, multipurpose kWh-meter is used for detecting events. Therefore this kWh-meter can be used at the same time for billing, power quality monitoring and appliance end-use monitoring. This prototype requires manual-setup in which the naming of appliances is done.

First a transient-passing step-change detector-software was developed. It segments the normalized power into periods in which the power is steady and periods in which it is changing. A period of change or event is detected if it exceeds a site-specific threshold-power. This software installed in a laptop PC connected via serial data bus to the power quality kWh-meter manufactured by Mittrix is used as recording equipment.

Secondly, load identification algorithms in order to identify different appliances by using the events recorded from total load were developed. These algorithms are able to identify two-state and multi-state appliances but appliances which are always in on-state and continuously variable appliances are outside the capacity of these algorithms. The software is installed in an off-line PC which means that it allows the analyzing of the data series as many times as necessary in order to develop and to test different kinds of algorithms.

The results of the NIALMS field testing in a real private house were verified by parallel measurements in the case of main appliances. The loads in the test house, in addition to being common household appliances, also contained one big multi-state load (hot water boiler for accumulating electrical heating). The average error of NIALMS in estimating daily energy consumption including nine main appliances was about 12.1 % and the average error of energy over a week period was about -6.2 %. Even information from the use of lights was recorded but the verification of results was impossible because of many different lighting loads. The above estimation errors are in the same range as other NIALMS-prototypes developed in France and in the United States although the exact comparison is impossible because of differences in power supply systems, appliance stock and number of tested households.

NIALMS has many application possibilities. Load research data concerning appliance load curves could be collected at moderate cost if a commercial NIALMS with remote reading capability would be available. For this application automatic-setup NIALMS should be developed. The results of DSM-programs or the influence of a direct load control signal could be verified with NIALMS by utilities. NIALMS is able to reveal device failures which might be evidenced by unusual power consumption or duty cycle characteristics. In commercial buildings NIALMS can be a part of a building automation system and non-intrusive electrical monitoring, combined with control signals issued by an automation system to offer valuable information for energy management and fault diagnostics purposes.

The future of NIALMS seems to be promising because of the deregulated energy market's need for better customer measurements is growing and more meters with non-intrusive abilities will apparently come on the market in the future. Product development work should first concentrate on the integration of event recording software into the power quality kWh-meter in order to get rid of the laptop PC at the monitoring site. This multipurpose kWh-meter with event recording functions in a customer's premises could be remotely read by a utility or third parties. More research work is needed in order to find better load identification algorithms especially for separating simultaneous events. In order to develop an automatic-setup NIALMS for the European market a large household appliance data base of power levels and duration of cycles should be collected.

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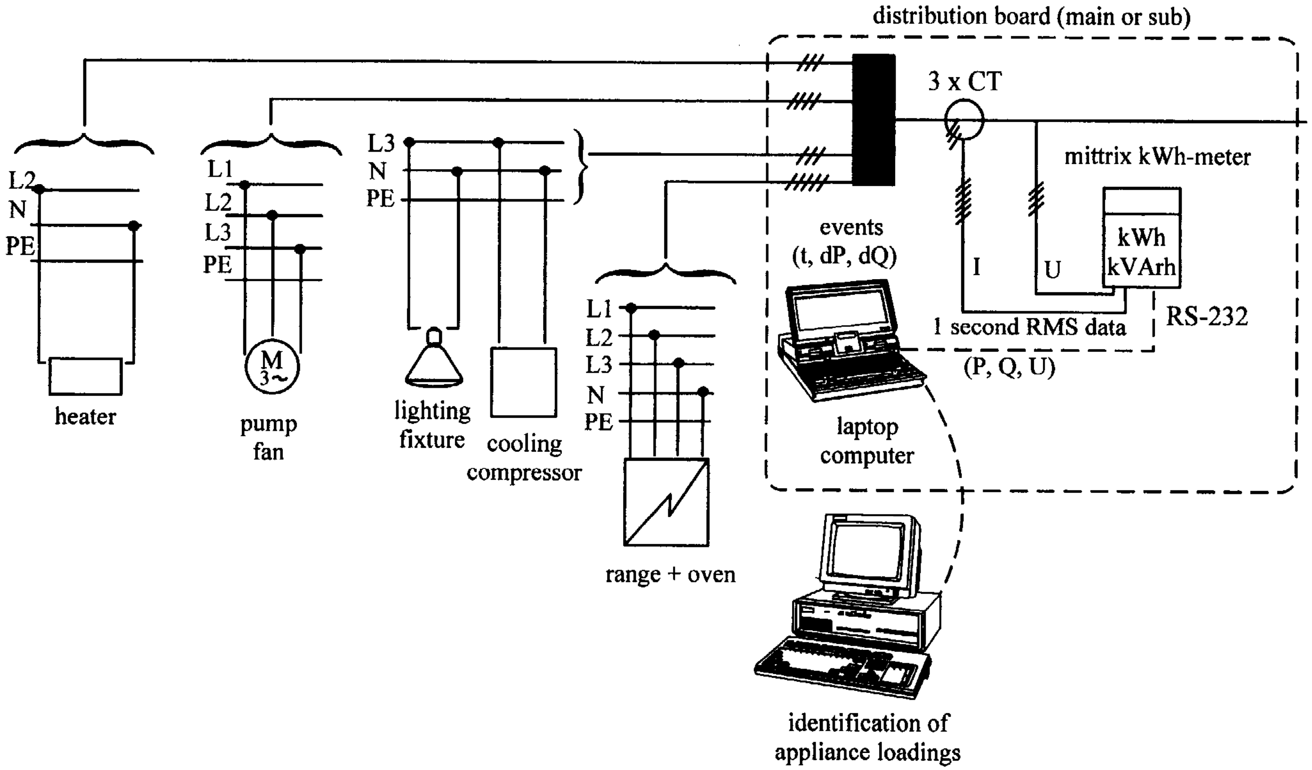
NIALMS-prototype



Daily electricity consumption of the test house during June 1996

Date	Total (Wh)	Small appliances	Range	Fluoresc. lights	Bread machine	Vacuum cleaner	Coffee machine	Toaster	Refrige-rator1	Refrige-rator2	Refrige-rator3	Water pump	Hot water boiler	Microwave oven	Dish-washer	Clothes washer	Others
1.6.1996	76266	4685	343	1009	0	0	86	34	1102	385	623	803	56601	104	90	0	10401
2.6.96	98900	4898	869	241	0	0	88	167	1207	410	630	299	77784	21	109	498	11679
3.6.96	63144	876	156	942	0	0	202	97	1513	412	656	89	45481	100	0	0	12620
4.6.96	73704	2690	31	846	0	60	185	98	1320	402	645	236	53385	39	124	566	13077
5.6.96	65112	1310	2060	1564	255	108	314	34	1488	428	674	327	43725	150	132	0	12543
6.6.96	77778	3743	726	324	0	0	218	294	1328	394	613	399	52878	63	114	0	16684
7.6.96	72536	398	0	611	0	0	180	97	1459	421	708	118	56361	24	0	0	12159
8.6.96	60596	623	1776	752	0	0	72	0	1434	429	692	318	38504	48	0	0	15872
9.6.96	53928	2304	176	447	0	0	226	0	1293	401	648	540	38698	0	0	0	9161
10.6.96	55898	1545	1316	545	0	0	200	0	1456	432	680	222	37926	0	0	0	11576
11.6.96	50932	2068	1400	187	0	0	331	0	1391	436	711	213	31878	25	95	0	12197
12.6.96	63813	1544	3504	200	0	0	176	0	1624	441	692	221	39936	74	102	609	14690
13.6.96	64034	1612	311	2451	0	0	184	0	1380	440	678	316	39509	24	0	1862	15267
14.6.96	64893	3563	975	1144	0	0	214	0	1430	398	652	188	45027	49	0	666	10587
15.6.96	87996	3624	2313	2858	4	291	214	100	1436	460	573	1644	57606	20	288	3016	13549
16.6.96	116033	4496	3215	814	0	0	496	0	1181	382	526	826	87912	178	268	1248	14491
17.6.96	74662	2108	1171	1596	0	0	229	128	1442	416	614	172	55684	55	111	0	10936
18.6.96	74348	2815	1359	1324	52	0	211	68	1092	413	584	206	24946	25	114	0	41139
19.6.96	78677	1678	1035	3	0	0	180	100	1602	410	620	242	39990	45	0	0	32772
20.6.96	71192	2063	1204	637	0	0	200	0	1567	437	588	134	52520	44	108	0	11690
21.6.96	71798	3856	3376	652	20	25	320	0	1436	454	587	628	49836	29	26	336	10217
22.6.96	80426	730	120	15	0	0	98	0	1374	423	577	72	66245	45	0	0	10727
23.6.96	80764	7183	1945	1554	0	0	215	33	995	378	475	1170	54575	6	111	2371	9753
24.6.96	72506	5206	375	438	0	0	163	0	1034	402	639	414	56310	30	138	0	7357
25.6.96	61297	1122	0	0	0	0	187	0	1392	434	639	109	48084	56	0	0	9274
26.6.96	72768	638	877	1609	0	0	187	0	1078	426	555	144	54428	25	116	482	12203
27.6.96	70801	1466	322	561	0	0	113	0	1280	443	584	131	56398	43	0	0	9460
28.6.96	68048	5066	745	1171	0	0	190	0	1219	410	580	407	48582	40	0	1800	7838
29.6.96	67574	2700	938	462	0	0	0	0	1374	474	587	674	48692	0	55	844	10774
30.6.96	89854	2826	2861	718	0	0	0	0	1110	493	562	5274	63841	0	0	0	11741
Sum (Wh)	2180278	79436	35499	25677	330	484	5680	1249	40038	12683	18591	16534	1523343	1364	2103	14298	402434
Sum %	100	3.6	1.6	1.2	0	0	0.3	0.1	1.8	0.6	0.9	0.8	69.9	0.1	0.1	0.7	18.5

APPENDIX 3

Daily electricity consumption of the test house during November 1996

Date	Total (Wh)	Small appliances	Range	Fluoresc. lights	Bread machine	Vacuum cleaners	Small cof-fee maker	Large cof-fee maker	Toaster	Refrige-rator1	Refrige-rator2	Refrige-rator3	Water pump	Hot water boiler	Microwave oven	Dish washer	Clothes washer	Others
1.11.1996	137093	6993	1539	1613	0	24	0	187	0	1248	606	441	497	109834	24	140	0	13947
2.11.96	141096	5856	1534	889	259	0	0	218	0	1524	471	528	259	112854	94	102	0	16508
3.11.96	118182	4524	844	1219	552	0	0	126	0	1262	576	466	1058	81953	168	61	720	24653
4.11.96	106906	3314	700	869	0	0	115	102	0	1217	546	539	84	85766	46	0	0	13608
5.11.96	96809	2305	1711	4	0	0	0	0	0	1272	483	484	272	73252	47	0	0	16979
6.11.96	100181	1007	1912	194	0	0	0	202	0	1457	487	559	108	76096	143	0	0	18016
7.11.96	100084	2532	1399	211	0	0	0	113	0	1159	502	492	310	74578	71	148	0	18569
8.11.96	113540	1393	182	764	0	0	0	190	0	1292	547	562	144	92829	49	133	0	15455
9.11.96	131148	4314	1066	1832	259	0	0	116	0	1334	468	458	785	106264	74	0	588	13590
10.11.96	152136	2443	2601	2006	20	0	224	265	0	1001	460	493	257	130293	65	224	0	11784
11.11.96	118876	4268	1736	1773	0	0	0	192	0	1375	434	486	190	95215	61	0	0	13146
12.11.96	144530	3040	312	746	0	0	0	213	111	1408	492	440	202	120082	0	0	0	17484
13.11.96	133793	2245	1606	1068	0	0	0	107	0	1236	488	475	291	110388	49	158	0	15682
14.11.96	120630	3079	975	742	0	0	0	176	0	1234	440	447	106	96030	24	0	0	17377
15.11.96	152058	1828	1098	2449	0	13	0	108	0	1368	472	528	147	127807	25	162	0	16053
16.11.96	121145	3001	299	5451	0	0	0	123	0	1266	496	452	628	94434	0	0	457	14538
17.11.96	144602	5278	2818	3212	258	0	0	210	0	1312	410	517	683	112126	31	274	975	16498
18.11.96	99498	3350	1291	1470	0	0	0	198	0	1314	487	448	109	75255	50	0	0	15526
19.11.96	108122	3387	2192	798	0	0	0	193	0	1398	488	412	193	82024	52	116	0	16869
20.11.96	110420	1183	1095	967	0	0	0	215	0	1378	486	482	415	86358	38	0	0	17803
21.11.96	121208	3721	1490	2286	0	0	0	180	0	1164	449	455	164	93129	0	0	0	18170
22.11.96	100085	586	110	1134	0	0	0	91	0	1360	504	482	136	80849	40	0	0	14793
23.11.96	122146	8042	2200	1204	258	26	156	208	0	1225	453	521	758	87432	19	101	0	19543
24.11.96	165195	5478	5964	1816	268	106	0	559	0	1340	395	478	401	129701	156	221	806	17506
25.11.96	108278	2698	171	584	0	0	87	308	0	1331	465	460	170	87187	81	133	0	14603
26.11.96	141750	2855	2362	1063	0	0	154	181	0	1310	511	391	209	114112	76	0	938	17588
27.11.96	153385	4733	993	376	0	0	193	284	0	1208	381	464	182	132010	110	144	0	12307
28.11.96	152148	4700	945	1726	0	0	88	210	0	1177	502	508	130	130480	39	0	0	11643
29.11.96	145974	5949	3142	4705	0	0	0	236	0	1274	455	471	205	120739	87	144	0	8567
30.11.96	147416	4545	2720	1797	0	0	225	304	70	1380	388	385	1201	115265	10	105	1255	17766
Sum	3808428	108646	47006	44967	1875	168	1242	5817	181	38824	14340	14325	10291	3034344	1728	2365	5739	476571
Sum %	100	2.9	1.2	1.2	0	0	0	0.2	0	1	0.4	0.4	0.3	79.7	0	0.1	0.2	12.5