D4.2.2 Power signatures of home appliances based on Non-Intrusive Appliance Load Monitoring (NIALM) method

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Summary

The importance of end-use load data is growing as the implementation of smart grids is emerging. More individual fault diagnosis and control of appliances is possible if the power consumption of these appliances is known in real time. Therefore simple monitoring method of appliances, like NIALM (Non-Intrusive Appliance Load Monitoring), is of great interest.

The Finnish company, MX Electrix Oy, has developed a device (IMU, Intelligent Monitoring Unit) which is able to monitor energy consumption, power quality and power events (appliance signatures) at the same time. Different applications based on this data can be implemented like connection of power quality problems to certain appliances, disaggregating total load into appliance loads, load-shed verification and activity surveillance of senior citizens in homes based on the use of appliances.

In order to develop above mentioned applications it is of great importance to know steady state models and power signatures of different appliances used in homes. Appliances that can be detected non-intrusively are classified into two main groups: 1. on/off- or two- state appliances and 2. multi- state appliances. In this document the power signatures of typical appliances of homes based on field measurements performed during many years are collected together. On- and off- switching of appliances can be shown as clusters in the dQ/dP-coordinate system.

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Preface

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Contents

1 Introduction

The importance of end-use load data is growing as the implementation of smart grids is emerging. More individual control of appliances is possible if the power consumption of these appliances is known in real time. Therefore simple monitoring method of appliances, like NIALM (Non-Intrusive Appliance Load Monitoring), is of great interest.

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 signaling) 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.

2 Overview of NIALM

2.1 Appliance signatures

The role of appliance signatures is the essence of the NIALM. Generally, 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 document. 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").

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.

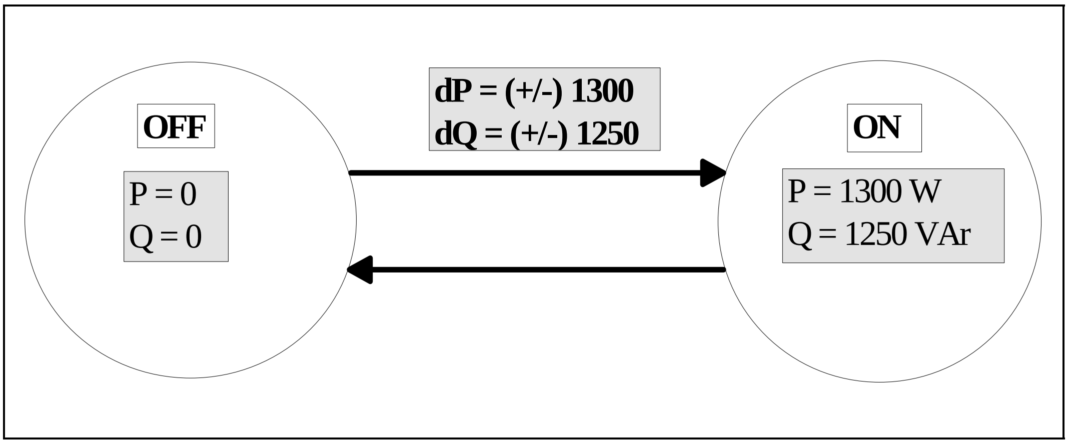

Fig. 1. An example of the operating states and state transitions of a two-state appliance (one on- and one off-state).

More information about the state of the art of NIALM and appliance signatures is available in reference (Pihala 1/2011).

2.2 Event recording

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 (Pihala 1998):

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

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 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.

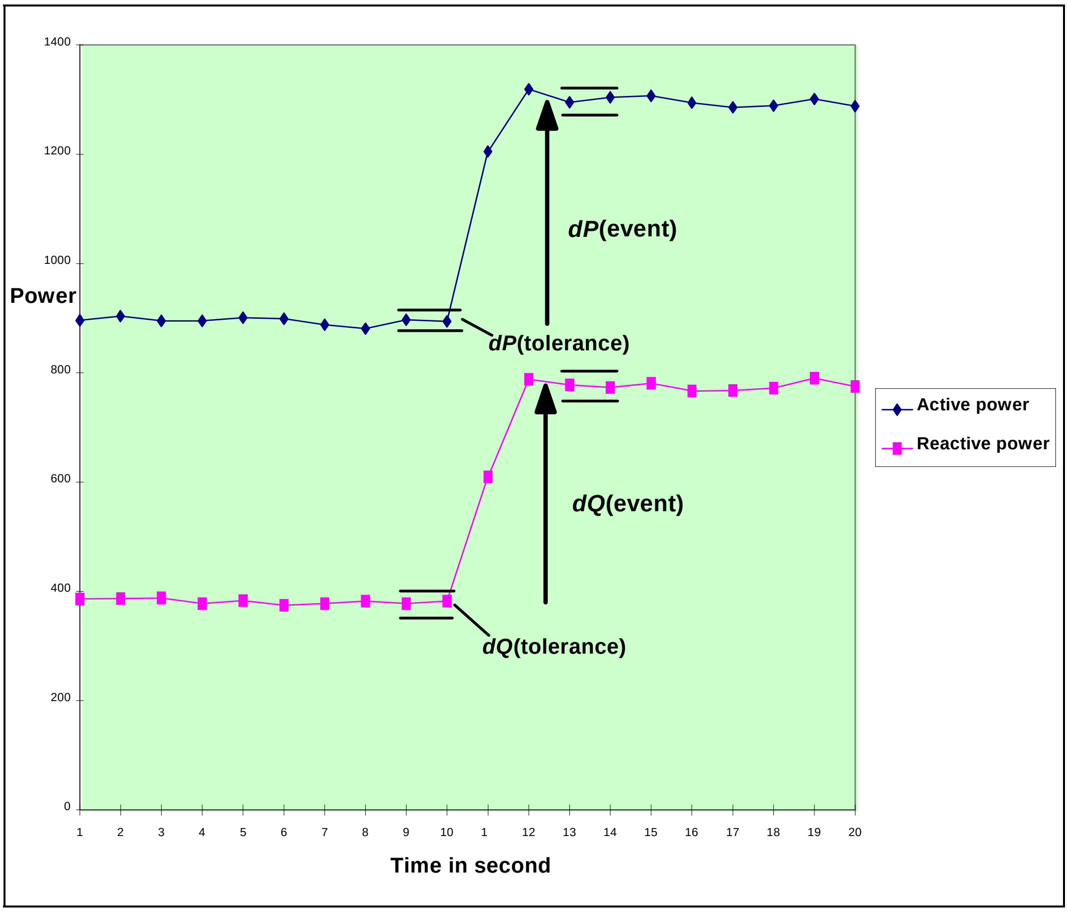

Fig. 2. Detecting an event in sample data caused by an appliance (Pihala 1998).

2.3 Event recorder

The Finnish company, MX Electrix Oy, has developed a device which is able to monitor energy consumption, power quality and power events (appliance signatures). This device is called in this document IMU (Intelligent Metering Unit, Fig 3.). IMU is able to measure the following quantities:

- Energy consumption:
  - active and reactive power
- Power quality (standard):
  - voltage levels, voltage un-symmetry, total harmonic distortion (THD)
  - un-even harmonics (3., 5., 7., jne)
  - frequency
  - outages
- Power quality (other):
  - DC-voltage, power factor, currents
  - 50 Hz:n active and reactive power
  - Voltage dips and swells
  - flicker
- Appliance signatures:
  - active and reactive power events with time marks

Fig. 3. Intelligent Metering Unit - IMU (MX Electrix Oy: EDFGL)

More information about IMU and its applications is available in reference (Pihala 2/2011).

2.4 NIALM system

The whole NIALM system consist of event recorder and software which is able to disaggregate the total load into appliance load curves (Pihala 1998). In order to develop accurate identification software of appliances much knowledge about appliance electrical behavior is necessary. Different load models and measured signatures of different appliances based on non-intrusive load monitoring method will be introduced in chapters 3 and 4.

2.5 Applications based on Intelligent Metering Unit

Power quality problems associated to certain appliances is possible to diagnose by using the power quality data and power signature data registered by the IMU at the same time. For example voltage dips are possible when appliances switch on.

Electricity use of appliances can be disaggregated from total load based on analysis of power signatures (on and off) of electrical appliances. Small power appliances (less than 50 W), appliances always on at the same power level and appliances changing power continuously can´t be monitored by NIALM based on step change recording. The accuracy of calculating certain appliance energy use from power signatures depends on the analysis method and the number of appliances monitored at the same time as well as the supply system (single or three-phase).

Smart-grid support for demand response lets electricity service providers shed loads during peak usage periods with minimal consumer inconvenience. Direct load control is a strategy in which consumers enroll appliances, such as electric water heaters, air conditioners, and electric vehicles, in a program to respond to load-shed instructions in exchange for a discount on electricity prices or other incentives. Direct control's effectiveness depends on the provider's ability to verify that appliances respond to load-shed instructions. Nonintrusive load monitoring, in which electric power meters identify loads generated by specific appliances, provides a practical strategy for load-shed verification in residences. Nonintrusive load-shed verification simplifies the trust assumptions required for direct-control deployment.

The activity of senior people in their homes can be followed based on the use of electrical appliances. This kind of surveillance can be carried out by using Non-Intrusive appliance load monitoring. Lights and kitchen appliances (cooker, microwave oven, coffee machine) are good examples of appliances which every household owns and which are typically manually switched on and off. The activity of power signatures of these appliances can be followed by NIALM and alarms can be generated if there are changes in these signatures. Reference (Pihala 3/2011) gives a detail analysis of NIALM-data from three senior apartments.

3 Appliance models

Appliances are electrically wired parallel on power lines (Fig.4). 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).

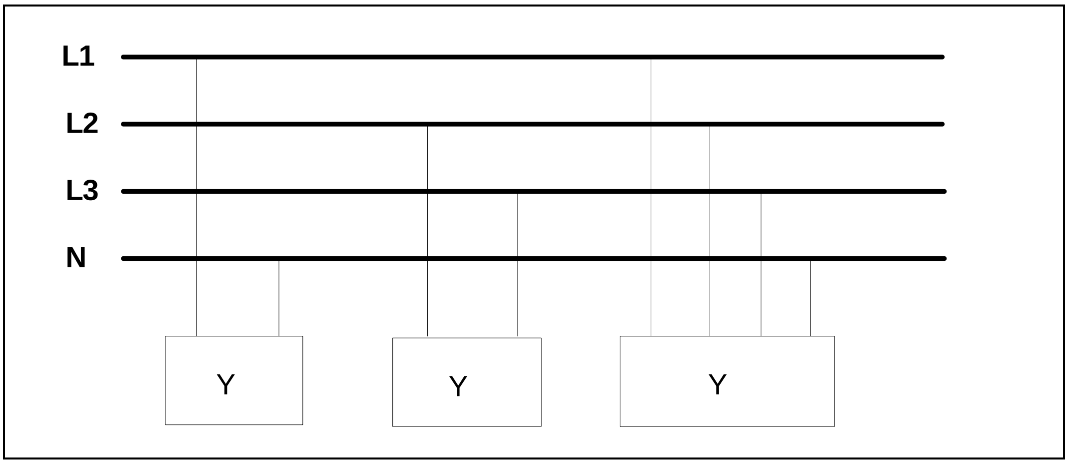

Fig. 4. Different possibilities to wire appliances (Y) on power lines in a three phase system (L+N, L+L or L+L+L+N)(Pihala 1998).

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

- on/off or two-state appliances (Fig 5a)
- multi-state appliances (Fig 5b).

There are also appliances that are difficult or impossible to detect non-intrusively like appliances that are always on or appliances that change their power continuously.

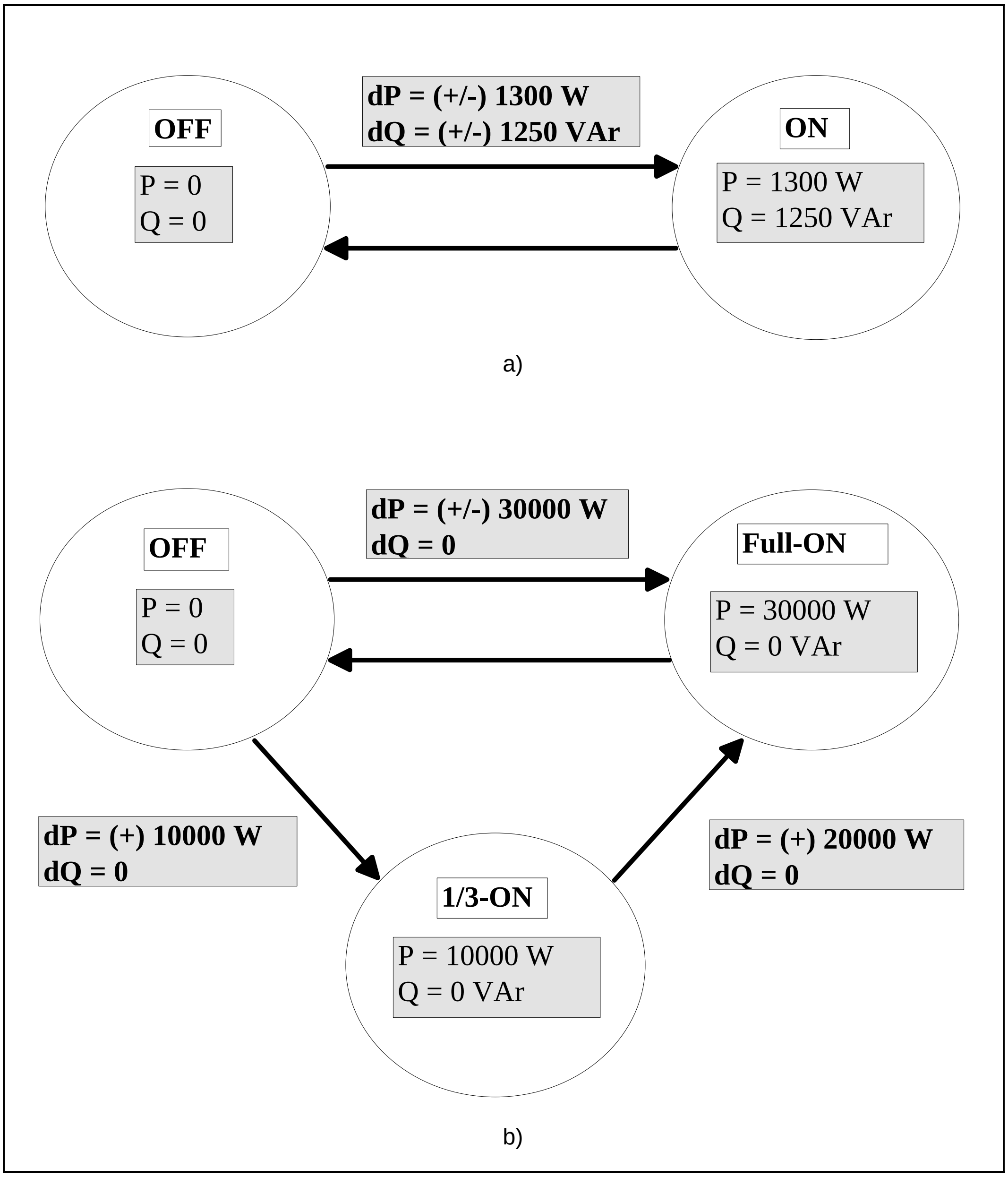

Fig. 5. Finite-state appliance models: a) generic two-state appliance, water pump b) multi-state appliance, hot water boiler (Pihala 1998).

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 6).

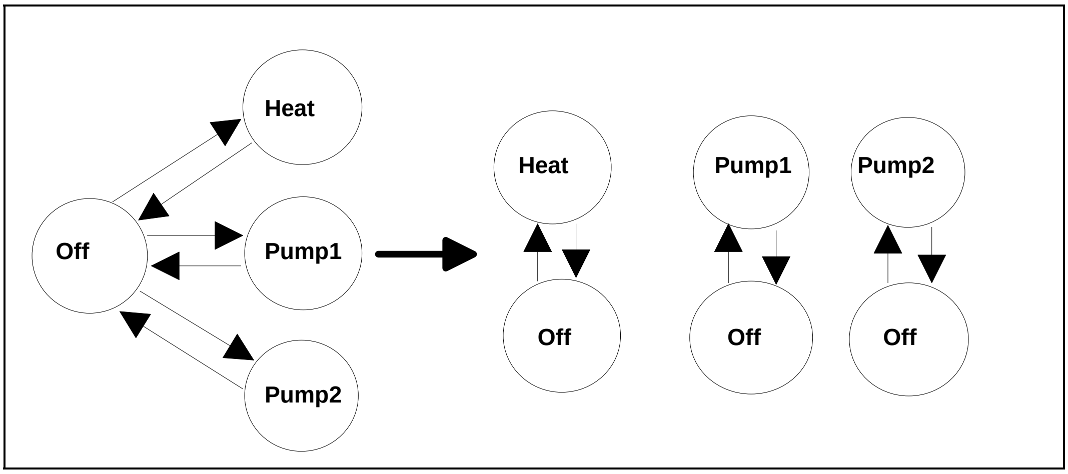

Fig. 6. Breaking a model of a dishwasher into many two-state models.

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. 7 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.

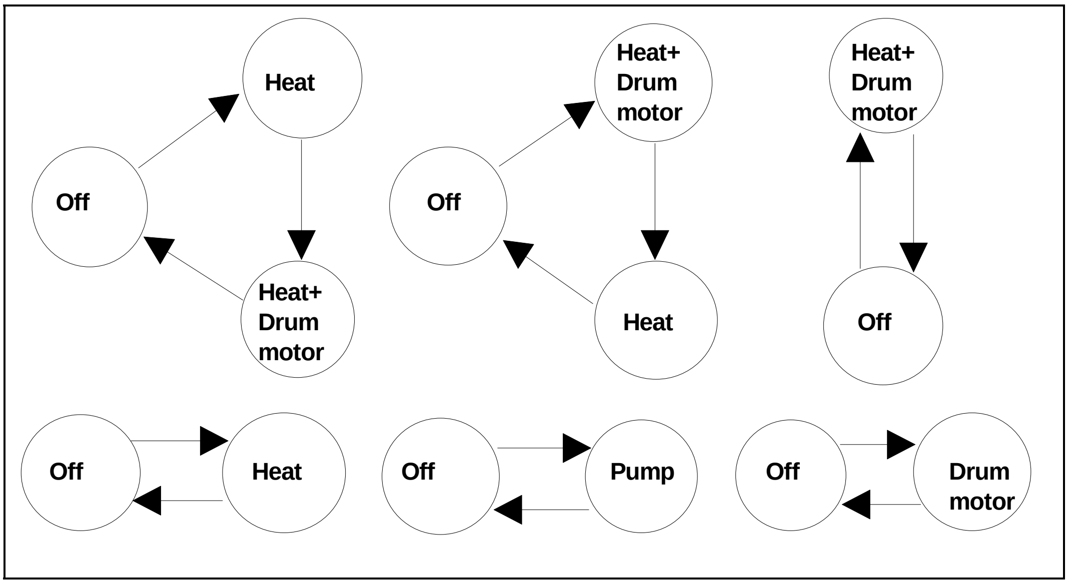

Fig. 7. Model of a typical clothes washer (Pihala 1998).

4 Power signatures of different home appliances

From the electrical perspective, depending on the specific product, the basic elements of an appliance can be grouped as shown in Table 1.

Table 1. Different electrical loads of appliances and their function.

Load	Function
Electronic Boards	User Interface and Control
Electro-Valves	Water/Fluid Flow
Pumps	Water Flow
Lamps	Lighting
Fans	Air Flow
Compressors	Fluid Flow
Motors	Drum Movement
Electric Heaters	Water/Space Heating
Magnetrons	Food Heating
Induction Heaters	Iron Plate Heating

When the appliance is in operation, these loads are managed in order to deliver the best result in terms of their main function performance (cooking, washing, heating etc.). Power signatures of these loads above 50 W can be recorded by NIALM, if the load keeps its certain power level at least about ten seconds. Therefore in the following described power signatures are steady state signatures.

4.1 Refrigerator and freezer

A refrigerator (often called "fridge") is a cooling appliance usually comprising a thermally insulated compartment and a compressor. The appliance cools its content to a temperature below ambient. Refrigerators are extensively used to store food which deteriorates at ambient temperatures.

The spectrum of domestic refrigeration appliances is wide. A refrigerator or a freezer has only one cooling compressor. A combination of a refrigerator and a freezer can have either one or two cooling compressor. Fig 8 shows a typical on-off cycling of one cooling compressor. During on-cycle the active power decreases and the re-active power remains almost constant. 15 W cycles in active power appear when the door of the measured appliance is open and the light inside the cabin is on.

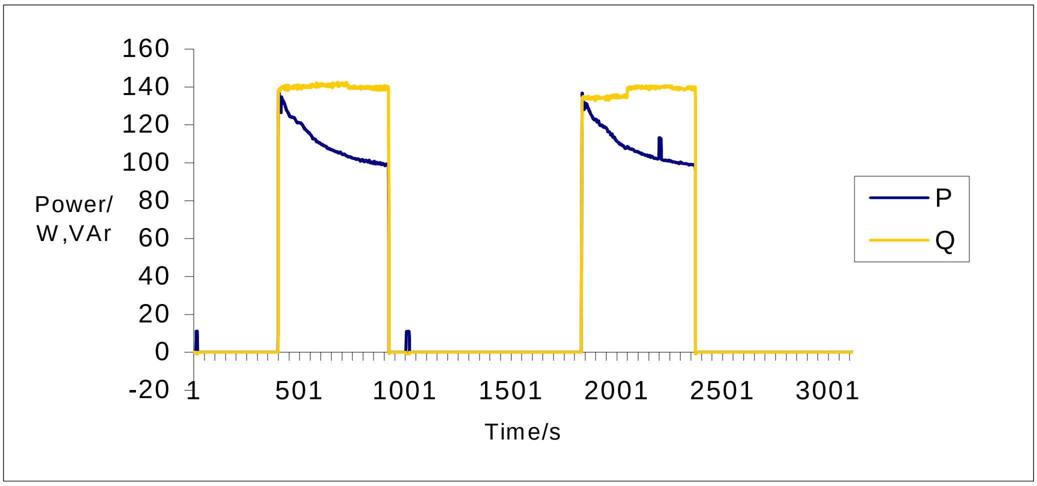

Fig 8. Cooling compressor cycles of a refrigerator (P active power, Q reactive power).

Fig. 9 shows the average on- and off- power signatures from 20 different freezers and refrigerators. Big volume of the device means bigger power signature compared to smaller volume devices. Freezers have bigger power signature compared to refrigerators.

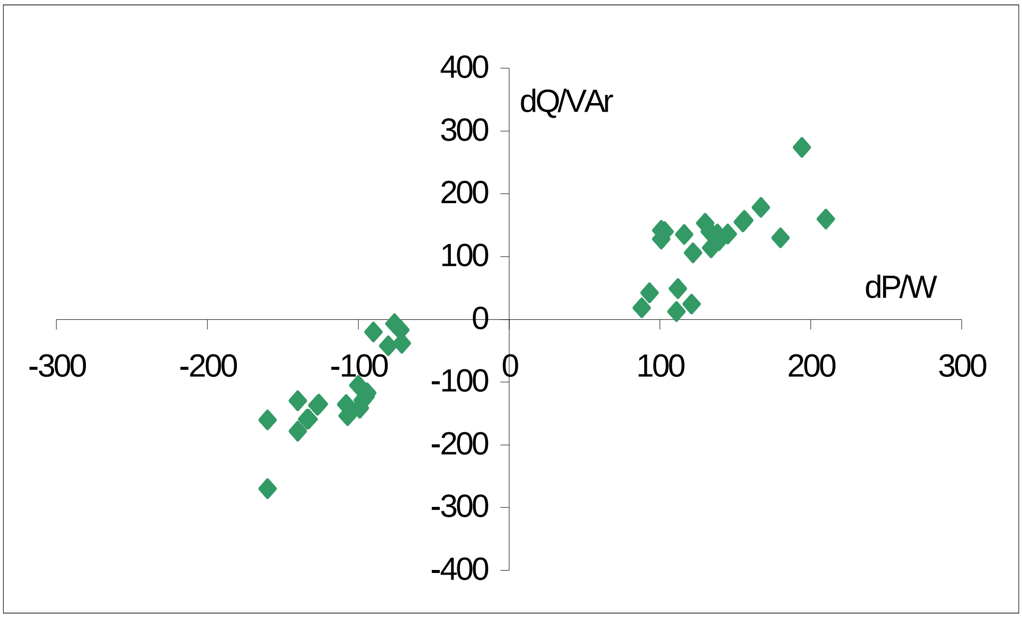

Fig 9. Average power signatures of twenty different domestic refrigeration appliances.

4.2 Dishwasher

Typical load curve of a dishwasher during one whole washing program is shown in Fig. 10. The main power consuming components are 1. a resistor for water heating (rwh), 2. a pump for water circulating (pwc), 3. a pump for water removal (pwr). In Fig. 10 the signature of rwh is about 1700 W, the signature of pwc is about 250 W and the signature of pwr is about 100 W. Simultaneous events of two appliances switching at the time happen in Fig 10. in time moments 2200 s: (pwc off, pwr on) and 3100 s: (rwh off and pwr on).

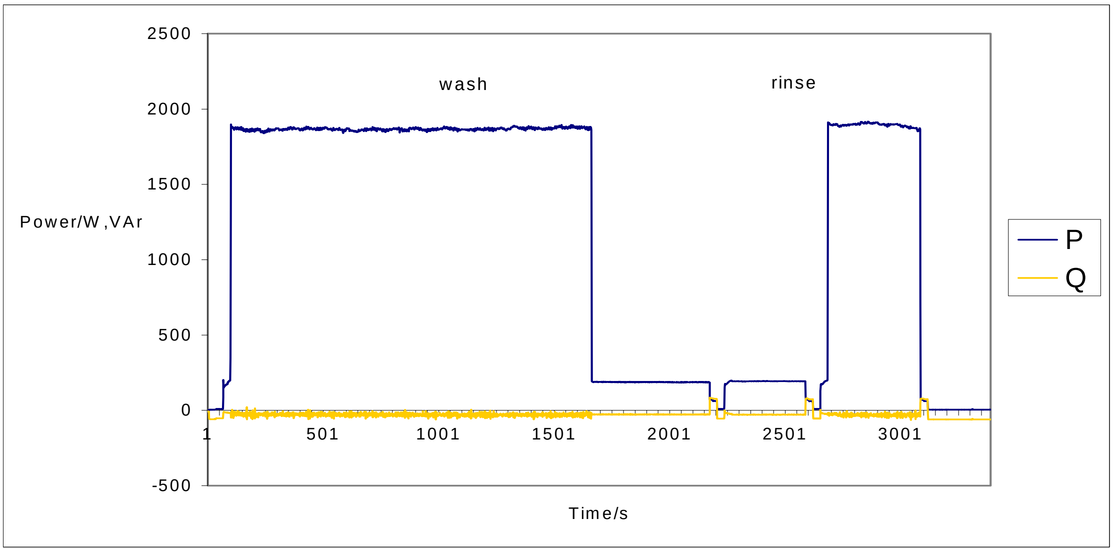

Fig. 10 Typical load curve of a dishwasher (P active and Q reactive power).

Fig. 11 shows the average power signatures of five different dishwashers. The power of resistors for water heating ranges from 1700 W to 2000 W. The active power of pumps is less than 150 W.

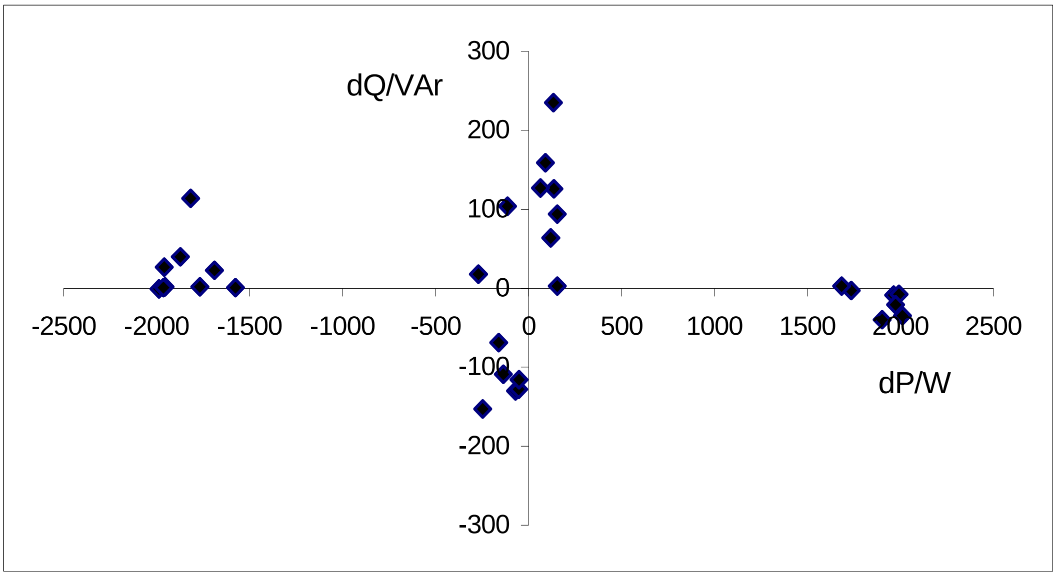

Fig 11. Average power signatures of five different dishwashers.

4.3 Clothes washer

Table 2 shows the energy consumed by different components of a clothes washer in different washing programs. Heating resistor dominates the consumption and also drum motor takes an essential part especially in higher temperature programs.

Table 2. Energy consumed by different component in different washing programs (Rissanen 1998).

Component	Temperature 40 °C Energy/Wh	%	Temperature 60 °C Energy/Wh	%	Temperature 90 °C Energy/Wh	%
Heating resistor	342	84	805	72	1275	77
Drum motor Rinsing	46 16	11 (4)	288 65	26 (6)	349 41	21 (2)
Water pump	14	4	6	1	10	1
Other	5	1	12	1	18	1
Together	407	100	1111	100	1652	100

Fig. 12 shows the last part of the washing cycle where the drum motor spins the clothes dry. The power level of the motor varies which means many different power signatures as shown in fig, 13. It shows the power signatures of twelve different clothes washers. Separate points in different quadrant far away from X-Y axis present simultaneous switching events of the water heating resistor and the drum motor.

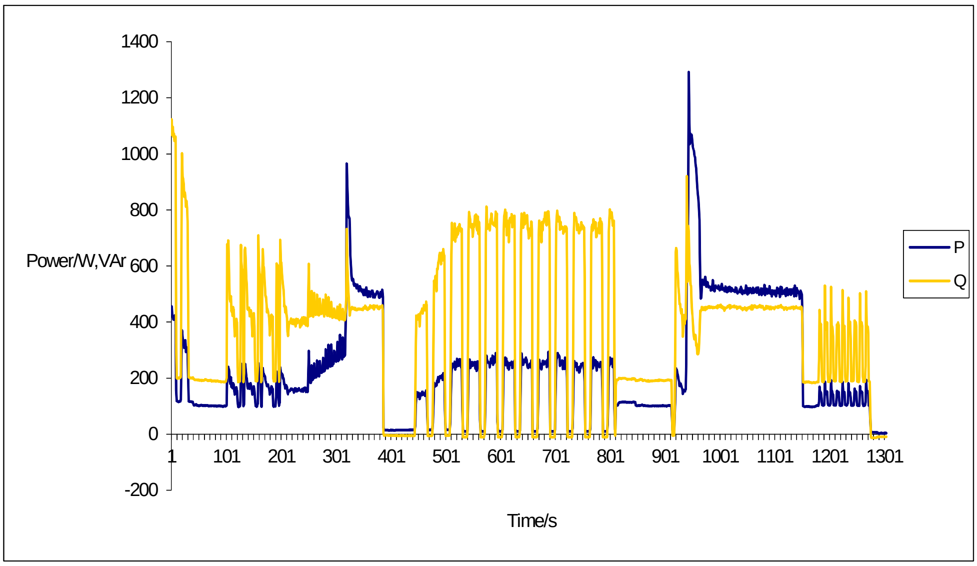

Fig. 12 Load curves of a clothes washer in last period (spin-dry).

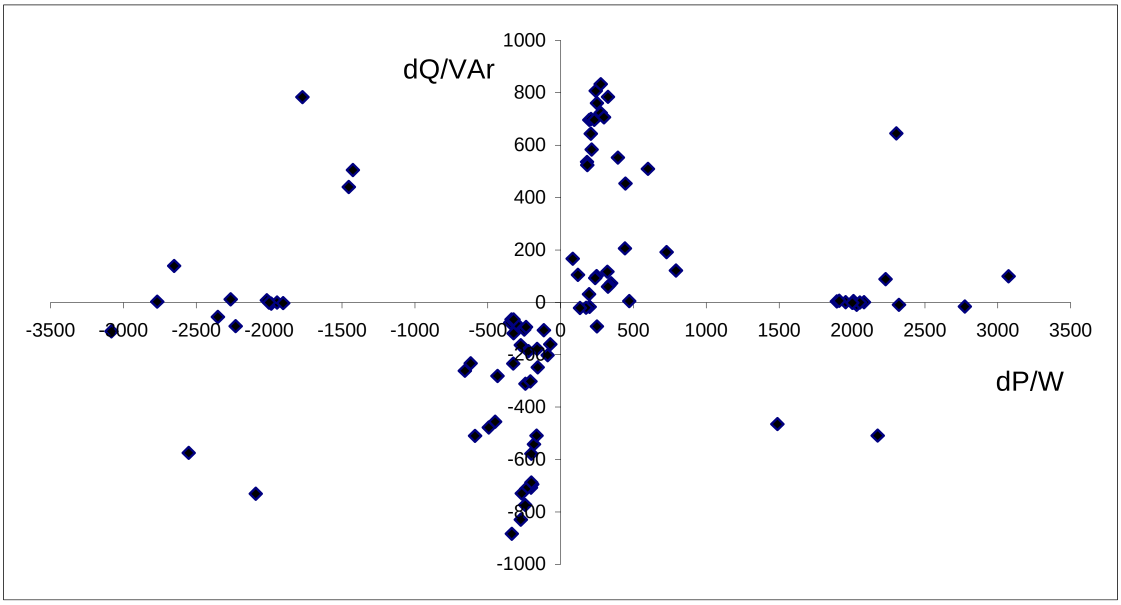

Fig. 13 Power signatures of twelve different clothes washers.

4.4 Microwave oven

Fig. 14 shows the load curve of a microwave oven at different power level and fig. 15 average power signatures of six microwave ovens.

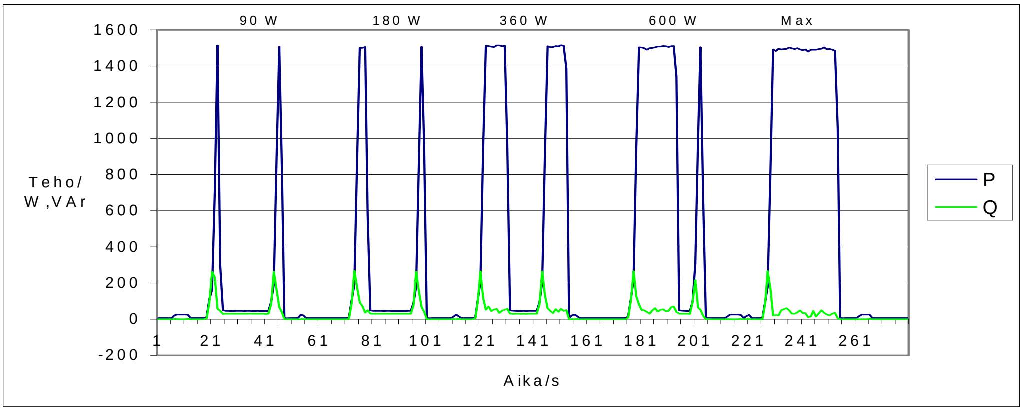

Fig. 14 Lload curve of a microwave oven at different power level.

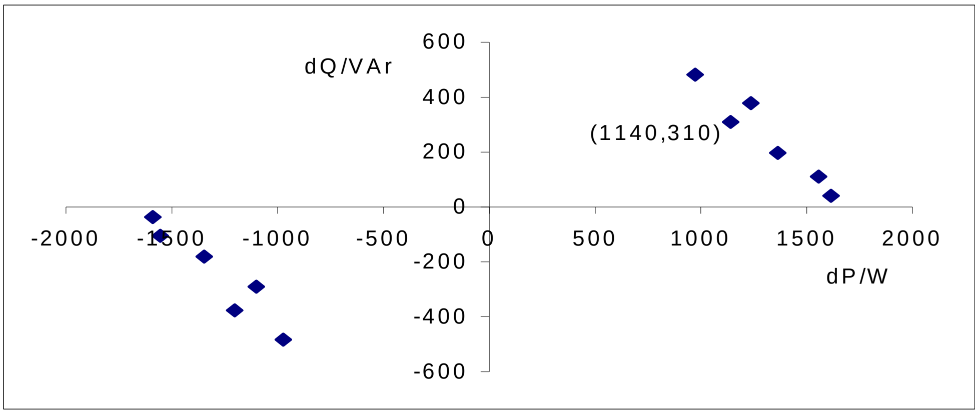

Fig. 15 Average power signatures of six microwave ovens.

4.5 Vacuum cleaner

Fig. 16 shows average power signatures of six different vacuum cleaners. They are very similar to signatures of micro wave ovens.

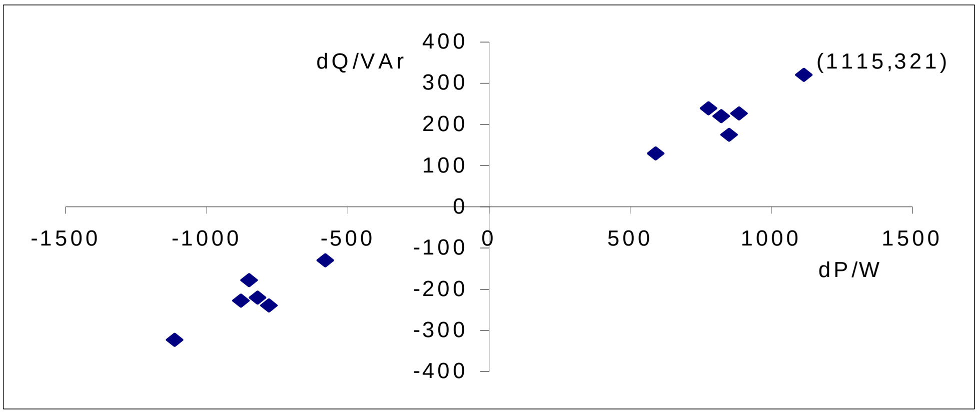

Fig. 16 Average power signatures of six vacuum cleaners.

4.6 Fluorescent lighting

Fluorescent lights are used in homes to some extent. Table 3 shows power signatures of some typical fluorescent lights. If the tube is supplied by conventional ballast without compensation capacitor it takes more reactive than active power. In the case electronic ballast reactive power taken/supplied from/to the electric network is small.

Table 3. On power signatures of different fluorescent lights. Tubes with conventional ballast except eb = electronic ballast (Rissanen 1998).

Tube Power (W)	Active power signature (W)	React. power signature (VAr)	Tube Power (W)	Active power signature (W)	React. power signature (VAr)
1x18	24	78	1x58	85	130
2x18	51	83	2x58	173	243
1x36	50	81	1x23 eb	24	-9
2x36	107	158	5x11 eb	57	-21

4.7 Electronic appliances

Computers and television sets are typical electronic appliances in homes. The power of these appliances is usually bigger than 50 W besides the power of laptop computers is under 50 W, which can't be monitored by NIALM.

The active power of a desktop computer can be from 50 W to 200 W depending on the capacity of a computer. The reactive power is capacitive (-10 VAr…-40 VAr). The active power of monitors can be from 20 W to 100 W depending on the type of displays.

The range of active power of television sets is quite wide depending on the type and size of TV sets (50 W…400 W). TVs have also a small capacitive power (-10 VAr…-20 VAr).

4.8 Other home appliances

In the following examples of power signatures of different home appliances (two-state) is given:

- kitchen hood 110 W, 80 VAr
- mixer 150 W, 20 VAr
- hair dryer 1170 W, 30 VAr
- bread maker, resistor 350 W
- bread maker, mixer 70 W, 35 VAr

4.9 Heat pumps

Most commonly, heat pumps draw heat the air (outside or inside air) or from the ground. The heat drawn from the ground is in most cases stored solar heat. Other heat sources include water; nearby streams or other natural water bodies have been used.

In Finnish households there are used basically the following three different main types of heat pump systems:

1. Geothermal (groundwater) heat pump system for space and hot water heating
2. Ventilation and heat recovery with combined heating of fresh air and hot water
3. Outside air source heat pumps for additional space heating. Basic space heating by direct electric heating (radiators or combination of room-specific heating elements

In the following an example from power signatures of a geothermal heat pump in a single-family house is shown. The floor area of the house is 200 m^2. Geothermal heat pump takes the heat from a deep (170 m) groundwater well. The house has water circulated under floor heating. Heat pump produces heat for space heating and hot water production.

The geothermal heat pump system has the following electrical components (rated power):

- Heat pump compressor, scroll-type 3200 W
- Pump for circuit of groundwater well 345…400 W
- Pump for circuit of under-floor heating 120…190 W
- Extra heater 6000 W

Fig. 17 shows the average three-phase power signatures of the heat pump compressor and the extra heater.

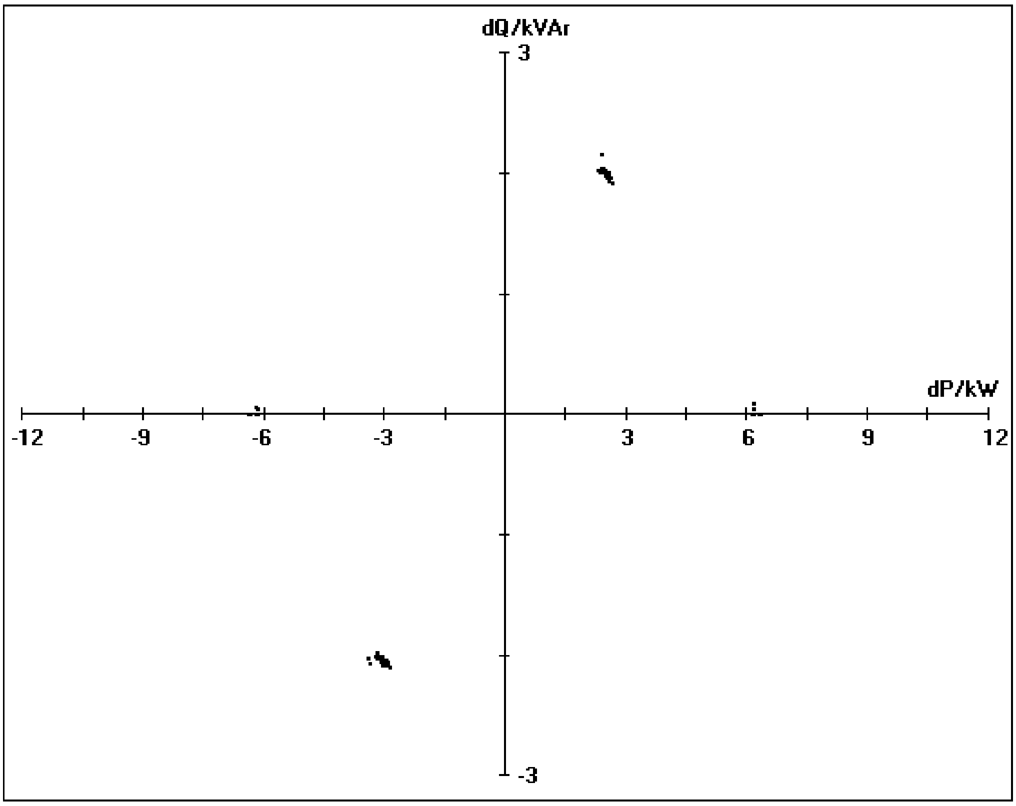

Fig. 17. The average three-phase power signatures of a geothermal heat pump compressor and the extra heater.

Fig. 18 shows the average three-phase power signatures of the heat pump compressor during a two months period in the spring when extra heater is no more needed. Separate points in the figure represent simultaneous events when the compressor and some other appliance switch on/off.

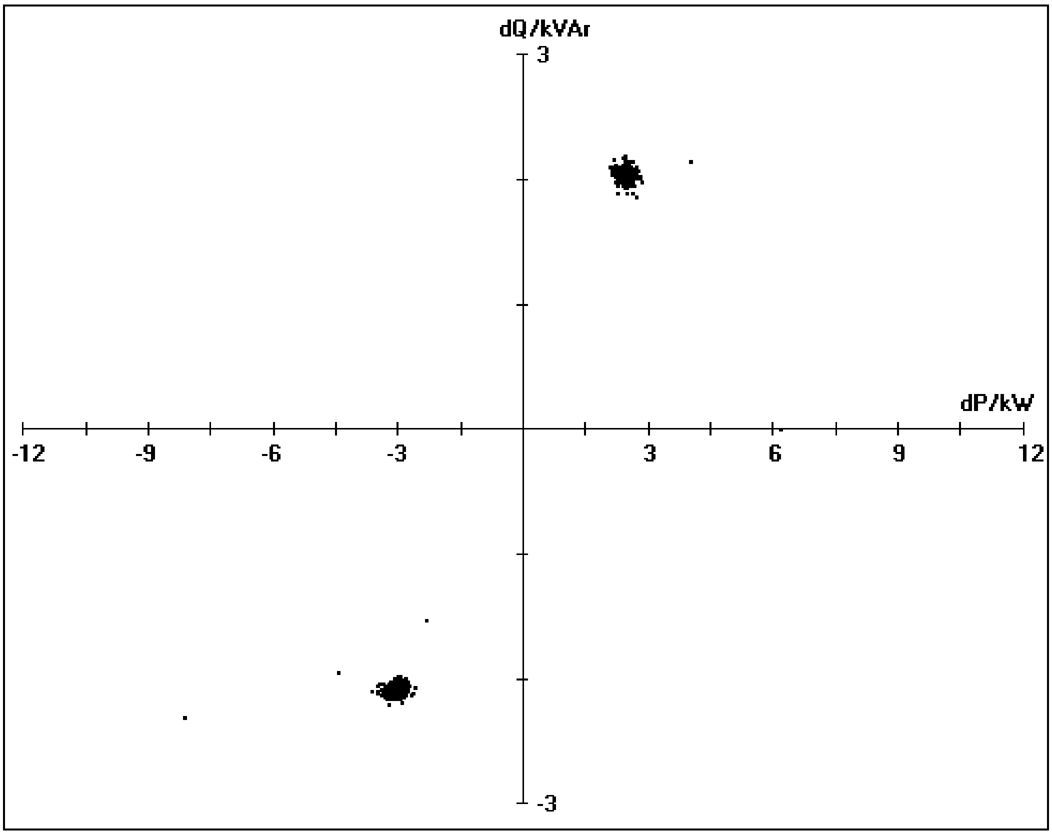

Fig. 18. Average three-phase power signatures of a geothermal heat pump compressor during two months in the spring.

In the following an example from power signatures of an active heating recovery system with heat pump in a single-family house is shown. This house has electric space heating with radiators. For production of hot water and ventilation there is a special system with heat pump: a ventilation and heat recovery system with combined heating of the fresh air supply and domestic hot water production. The system ensures controlled and balanced ventilation. It produces hot water and heats the fresh air entering the house. The heat energy in the exhaust air leaving the house is recovered by means of a heat pump and is used for production of hot water and heating of the fresh air. The exhaust air flows through a duct system to the heat pump where the energy is recovered.

In “Energy-mode” the system operates with a surplus of exhaust air until the desired water temperature is reached which ensures faster heating of the water. In “Comfort-mode” exhaust and fresh air volumes are balanced and the heating of the fresh air has priority over the hot water production. The cooled exhaust air is discharged to the outside. The unit has a 180 litre hot water tank and two ventilators for transportation of the fresh and exhaust air. For hot water production also an extra electric heater of 1000 W is installed for production of hot water during peak demand periods.

The system has the following electrical components:

- Heat pump compressor 315…495 W
- Two fans, step 1…4 28…106 W
- Extra heater 1000 W

Fig. 19 shows the average power signatures of the heat pump compressor and the extra heater.

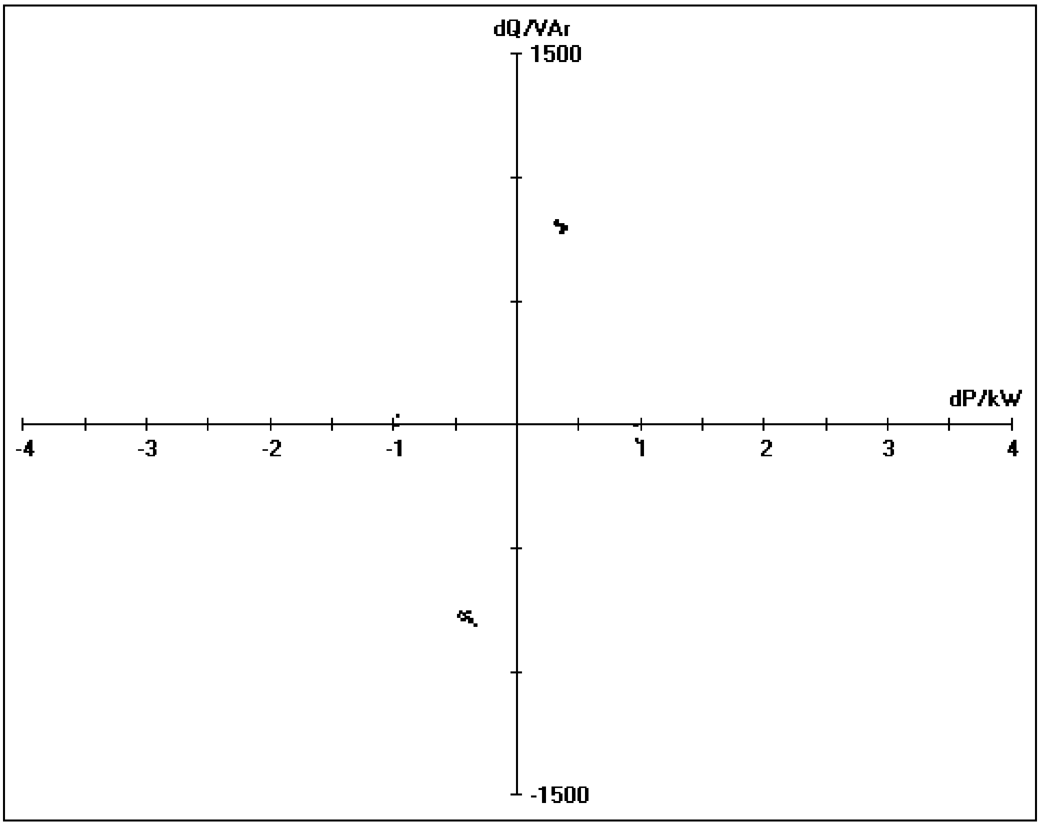

Fig. 19. Average power signatures of an active heating recovery heat pump compressor and the extra heater.

The last example from heat pumps is outside air source heat pump for additional space heating. Basic space heating is produced by direct electric heating (radiators or combination of room-specific heating elements). Fig. 20 shows power signatures of an inverter based on air source heat pump during three days. Because of the compressor supplied by an inverter the power changes often and no clear clusters of power states doesn’t exist. This makes the identification of this appliance very challenging. In practice the power changes also continuously and therefore recording based on steady state of power monitoring can’t be applied for energy monitoring of this kind appliances. Inverter based application needs to monitored separately by intrusive methods. Actually the data shown in fig.20 can make the identification of other appliances supplied by the same phase as an inverter more difficult.

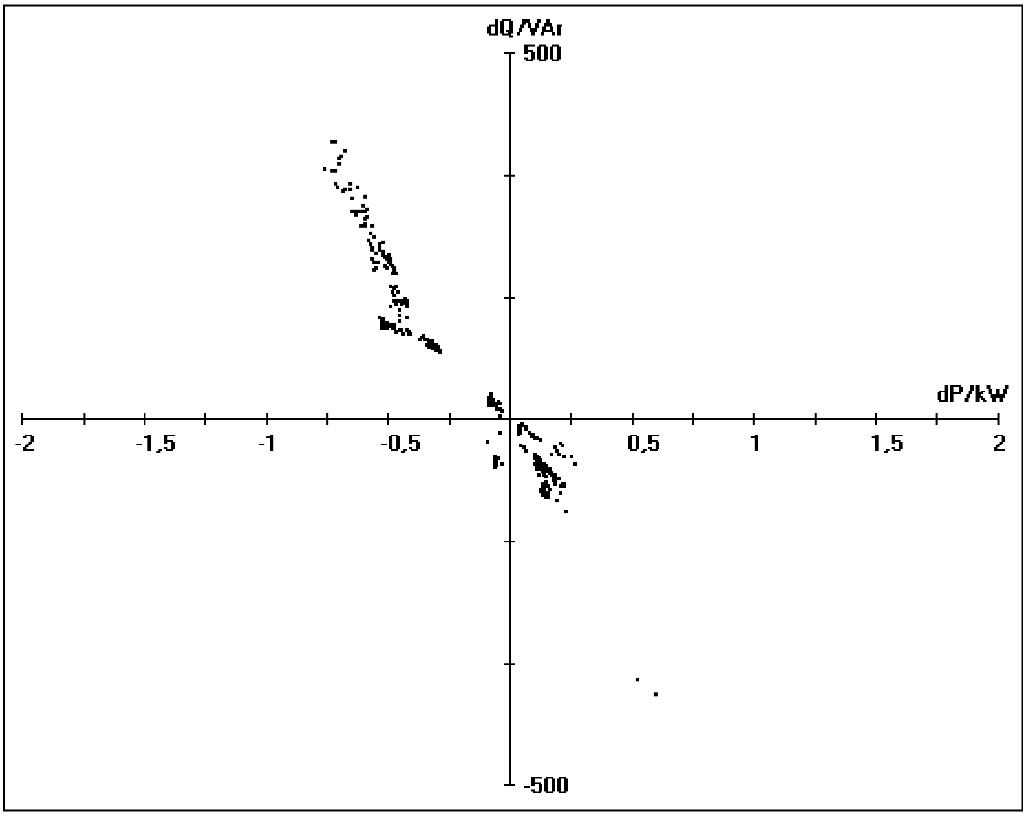

Fig. 20. Average power signatures of an inverter based air source heat pump.

4.10 Inductive heating

Electric range with inductive heating plates is still quite rare in Finnish homes. This kind of heating is possible if containers manufactured from ferromagnetic material is used for food heating. Heating stops automatically when the container is removed from the plate.

Fig. 21 shows an example from a load curve of inductive heating when two liters of water is boiled in a kettle. Boiling starts at time moment 1200 s and the water boils at the end of time scale (1601 s). In the beginning the plate is switched on full power (12/12). Power change is 1400 W and -90 VAr. When boiling starts the plate automatically transfers to a smaller power state (1300 W). At time moment 1350 s the power manually switched to power 6/12. After that no more stable state exist until at time 1560 s the power is manually switch on 10/12. After 25 seconds the power is switched manually to 9/12 and vibration of power begins again. This kind of power behavior makes identification of appliance very difficult.

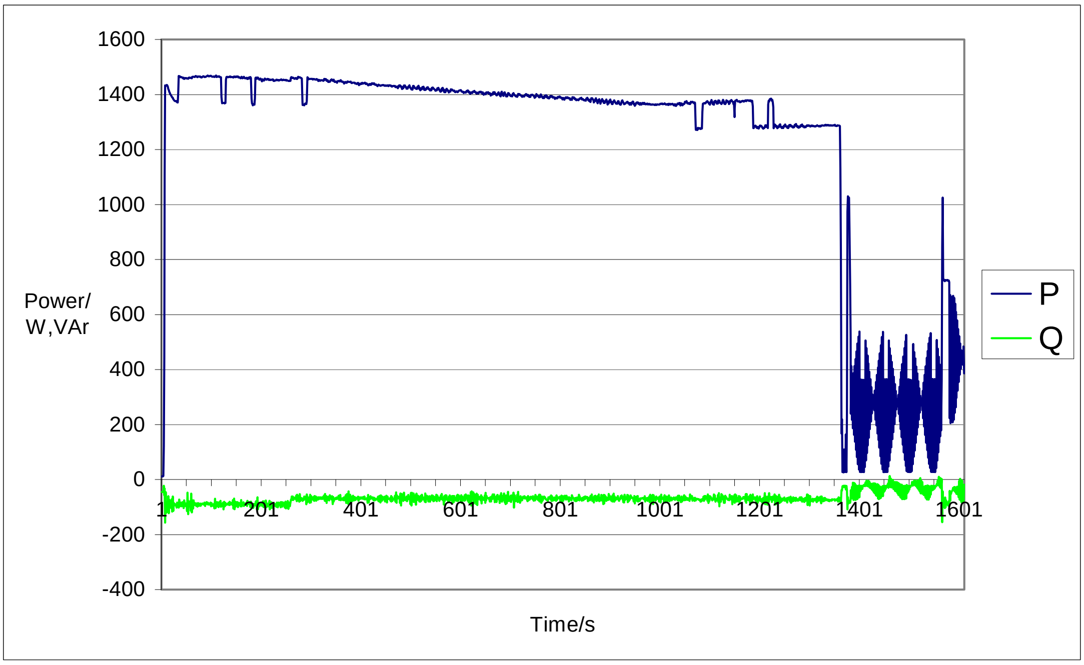

Fig. 21. An example of a load curve of inductive heating of water in a kettle.

4.11 Sauna

In Finland electric saunas are typical in homes. Sauna stoves have typically three resistors, one in every phase. The nominal power of stoves ranges from 6 kW to 12 kW depending on the volume of the sauna. The stoves have no reactive power.

Thermostat in the sauna controls the temperature. Usually all power is switch on and off. Power signature of this kind of control is one on and one off event. Fig. 22 shows a more complicated situation where the thermostat controls each phase separately. Therefore power signatures of this stove include one three phase on/off -event (± 6 kW) and every phase have one single phase on/off –event (± 2 kW).

Fig. 22. An example of load curve of a sauna stove controlled by a multistate thermostat.

4.12 Hot water boiler

Hot water boiler has resistors which heat the water. If water is not used for heating of the house the volume of hot water boiler ranges from 50 liters to 300 liters. The nominal power of resistors ranges from 3 kW to 6 kW (three phase).

If hot water is also used for heating of the house the volume of water storage ranges from 1000 liters to 3000 liters. In this case the nominal power of resistors ranges from 9 kW to 30 kW (three phase). Electricity for heating is used only during night time to heat the water in the storage. Fig. 23 shows an example of load curve of hot water boiler which is controlled on 1/3 power by Distribution System Operator (DSO) in the evening and the last 2/3 power later in the night. When the boiler is fully charged thermostat switches the load off. Later in the night thermostat controls the load. State transition model of this hot water boiler is shown in Fig 5 b).

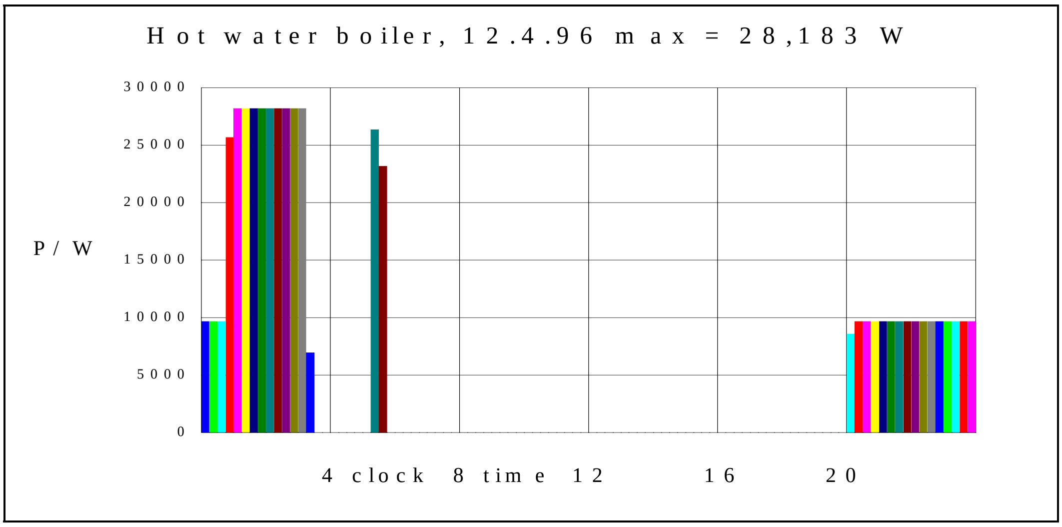

Fig. 23. An example of a load curve (15 min average power) of a hot water boiler controlled by DSO and thermostat (Pihala 1998).

4.13 Summary of power signatures

Power signature clusters of common single-phase home appliances are shown in Fig. 24. Especially in the area of active power less than 200 W there are many overlapping clusters.

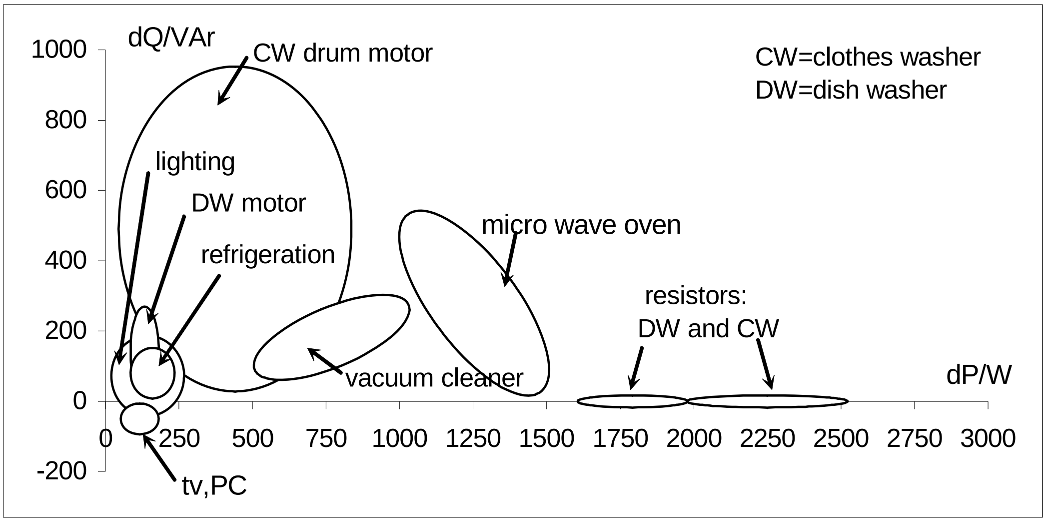

Fig. 24. Power signature clusters of common home appliances (Rissanen 1998).

5 Summary

The importance of end-use load data is growing as the implementation of smart grids is emerging. More individual fault diagnosis and control of appliances is possible if the power consumption of these appliances is known in real time. Therefore simple monitoring method of appliances, like NIALM (Non-Intrusive Appliance Load Monitoring), is of great interest.

The Finnish company, MX Electrix Oy, has developed a device which is able to monitor energy consumption, power quality and power events (appliance signatures). This device is called in this document IMU (Intelligent Metering Unit).

By using the data registered by IMU it is possible to develop new useful applications for smart grids. Power quality problems associated to certain appliances is possible to diagnose by using the power quality data and power signature data registered by the IMU at the same time. Electricity use of home appliances can be disaggregated from total load based on analysis of power signatures (on and off) of electrical appliances. Nonintrusive load monitoring, in which electric power meters identify loads generated by specific appliances, provides a practical strategy for load-shed verification in residences. The activity of senior people in their homes can be followed based on the use of electrical appliances. This kind of surveillance can be carried out by using Non-Intrusive appliance load monitoring. Lights and kitchen appliances (cooker, microwave oven, coffee machine) are good examples of appliances which almost every household owns and which are typically manually switched on and off.

In order to develop above mentioned applications it is of great importance to know steady state models and power signatures of different appliances used in homes. Appliances that can be detected non-intrusively are classified into two main groups: 1. on/off- or two- state appliances and 2. multi- state appliances. In this document the power signatures of typical appliances of homes based on field measurements performed during many years are collected together. On- and off-switching of appliances can be shown as clusters in the dQ/dP- coordinate system. In a single house power signatures in each phase are measured and from this data symmetrical three phase loads are easily separated in to an own time series of events.

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