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Observer based Model Identification of Heat Pumps in a Smart Grid

P. Andersen, T. S. Pedersen, K. M. Nielsen

Abstract— **The extensive growth of installed wind energy plants in Denmark leads to increasing balancing problems in the power grid due to the nature of wind fields and variations in consumption. One way to overcome these problems is to move consumption to times where wind power otherwise cause overproduction. A part of a solution can be to take advantage of floor heat capacity in single-family houses using heat pumps. This large heat capacity makes it possible to move consumption without compromising the comfort of house residents. In a Danish research project a virtual power plant using centralized control of a large number of houses with heat pumps is established. In order to make the control algorithm a vital part is a dynamic model of each house. The model predicts the house indoor temperature when heat pump power and outdoor temperature is known. The model must be able to describe a large variety of heat pumps and houses. In the paper a house model and a method to identify the model is presented. The Kalman observer models are optimized using measurements from real houses.**

I. INTRODUCTION

In recent years problems with balancing electricity supply and demand in the grid has emerged in Denmark. The problem is mainly due to the large and fluctuating power production from wind turbines. This problem will grow in the near future due to an increased number of wind turbines. In Denmark at present wind power meets 20 % of the electricity demand, however this covers variation from a minimum of 2-3 % to peaks more than 100 % of the instantaneous power demand. The Danish government wants the wind energy percentage to be lager than 50 % in 2020. The transition from use of fossil fuels to renewable energy sources is thoroughly treated in [1],[2] and [3].

A solution to solve the balancing problem is to use already existing storage possibilities like the heat capacity in the single-family floor heating systems. In latest decade almost all new single-family houses built in Denmark have been equipped with floor heating systems instead of conventional radiator systems, see [4] . Outside the central heating areas a new subsidy where oil-fired burners may be replaced by heat pumps is valid at the moment. On the Danish Finance Act for 2010 an amount of 400 million DKR is allocated for this purpose [5]. The Danish Energy Agency estimates that more than 50.000 small heat pumps are installed for heating single-family houses corresponding to 6-7 % of the total electricity consumption [6]. At the moment more than 25.000 small heat pumps are installed every year [7]. The small heat pumps are used outside the district heating areas which cover about 54 % of the total heat consumption in Denmark [8].

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The large number of floor heated houses using heat pumps gives a huge heat capacity due to thick concrete floor layer. If the owners of these houses will lend this storage capacity to the balance responsible some of the balancing problems may be solved. With only a small loss of comfort for the house residents consumption can be moved to times where the production of renewable energy is high, at the same time giving lower consumption when the production is low.

This work is a part of IFIV (Intelligent remote control of individual heat pumps) a Danish funded demonstration project where the principles will be used in 10 single-family houses. Here the objective is to investigate the potential for using the floor heat capacity to balance the production and consumption without discomforting the house residents. The main idea of the IFIV project is to implement a Virtual Power Plant by centralized control of the individual heat pumps, making it possible for a trading company to move the power consumption in time taking the residential comfort and energy prices into consideration. This optimization requires a dynamic model of the individual houses and on-line access to house measurements. The main issue of this paper is to identify a proper dynamic model of the houses.

The houses in question have different thermal characteristics and only a limited number of transducers. At the same time many of the houses are equipped with alternative energy sources such as wood stoves, solar panels etc. Typically these power inputs are not measured even though they give a substantial contribution to the total energy supply of the house. Therefore the model must cope with normal heat pump heated houses as well as houses with combined energy supply systems. In this paper the main topic is to determine a model structure that may be used for many different house types. The model structure must be well suited for parameter identification based on few measurement points. The main problem in the model identification is to estimate house parameters such as heat capacity and heat transfer coefficients and at the same time determine the unknown energy inputs. The chosen model structure and identification algorithm are tested on a number of Danish heat pump equipped single family houses.

The paper is organized as: Section II gives a description of the control of heat pumps arranged in a smart grid. Section III describes the actual ground heat pumps and a new control box able to connect to the internet. Section IV discuss modelling of the house and observer based identification. Section V shows results of model identification; finally we conclude the paper in Section VI.

II. Description of a smart grid heat pump control system

In figure 1 the online access between a house and the trading company is illustrated. The house is equipped with house sensors such as room air temperature sensors, water temperature and flow sensors for the heat pump. A control box measure the sensor signals and activate the heat pump. The control box is connected to the trading company using the internet. The trading company controls the heat pumps in the individual houses using information about weather, prices for electrical power and the states for the houses. Prices for electrical power reflects the estimated production and consumption of power for the Nord Pool area for a 24 hour time slot. Using the prices, weather forecast, house states and a dynamic house model the trading company calculates an optimal power consumption hour by hour for each house. The model in focus is intended to be used in an optimization algorithm placed in a local balance responsible's (LBR) computer system as shown in figure 1.

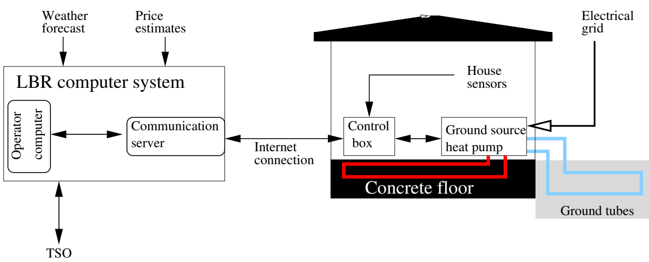

Fig. 1. The computer system of the trading company and a single-family house.

In this context the residential comfort is equivalent to one indoor temperature in a appropriate position . The purpose of the dynamic model is to predict the indoor temperature as a function of heat pump power, weather conditions and alternative heating sources as wood stoves, solar panels, domestic appliances etc. It should be noticed that individual house models are needed. The model may be formulated as

$$\begin{aligned} T_a(t) = F(&w_{hp}(t), w_{sun}(t), w_{add}(t), \\ &T_o(t), 'house \quad parameters') \end{aligned} \tag{1}$$

F is an integral equation system which maps time dependent functions and parameters into the T_a. T_a is the room (comfort) temperature, w_{hp} is the heat pump power,w_{sun} is solar power, w_{add} is additional power (wood stove etc.), T_o is ambient temperature. The input for the purchase tool is a weather forecast giving an estimate of the outdoor temperature and the solar radiation 12 to 36 hours ahead of the bid situation. The additional power w_{add} is unknown as well as the house parameters.

Another part of great importance is estimates of the prices of electrical power in the mentioned time window. These estimates will not be further treated in this paper but trading companies have extensive experience of how wind turbine power production and weather influence prices.

In the IFIV project a total control system is established, a detailed description may be found in [11], [12]. Other optimal solutions may be found in [9] and [10]

The purchase of power may be formulated in an optimisation context where a function, P (DKK), to minimize is given by

$$\begin{aligned} &P(w_{hp}(t), \Upsilon_p(t), \Upsilon_{Tp}(t), T_a(t)) \\ &= \sum_{t=1}^{24} w_{hp}(t)\Upsilon_p(t)h + |T_{a,ref}(t) - T_a(t)|\Upsilon_{Tp}(t)h \end{aligned} \tag{2}$$

Υ_p (DKK/(Watt hour) is the estimate of the price of power. Υ_{Tp} (DKK/(^oC hour)) is a factor that weight between cost and discomfort, meaning that a large value will force an optimizing algorithm to keep the temperature near the reference temperature, $T_{a,ref}$, and a small value will give the lowest cost. h is the time slot which is often one hour.

It should be noticed that the power from the heat pump is the sum of the power to the floor w_{fh} and the power to the heated water w_{hw}

$$w_{hp} = w_{fh} + w_{hw} \tag{3}$$

The optimum is found to

$$w_{hp,opt}(t) = \arg \min_{w_{hp}(t)} \left[P(w_{hp}(t), \Upsilon_p(t), \Upsilon_{Tp}(t), T_a(t))\right] \tag{4}$$

subject to

$$\begin{aligned} T_{a,min}(t) < T_a(t) < T_{a,max}(t) \quad \forall t \in \{1, \cdots, 24\} \\ 0 < w_{hp}(t) < w_{hp,max} \quad \forall t \in \{1, \cdots, 24\} \end{aligned}$$

where $T_{a,min}$ and $T_{a,max}$ are the smallest respective the largest value allowed for the room temperature in order to be within the comfort level and $w_{hp,max}$ is the max. heat pump power.

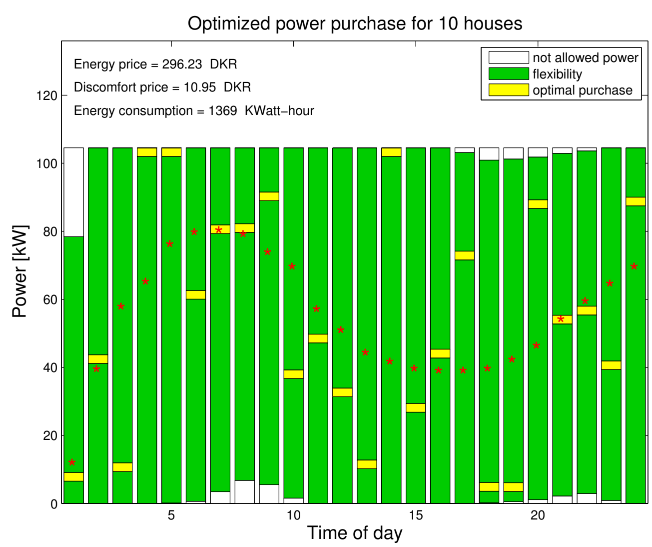

Fig. 2. Optimized power purchase for ten houses. Yellow is predicted optimized energy purchase, green is flexibility and red is power if the room temperature is keept constant.

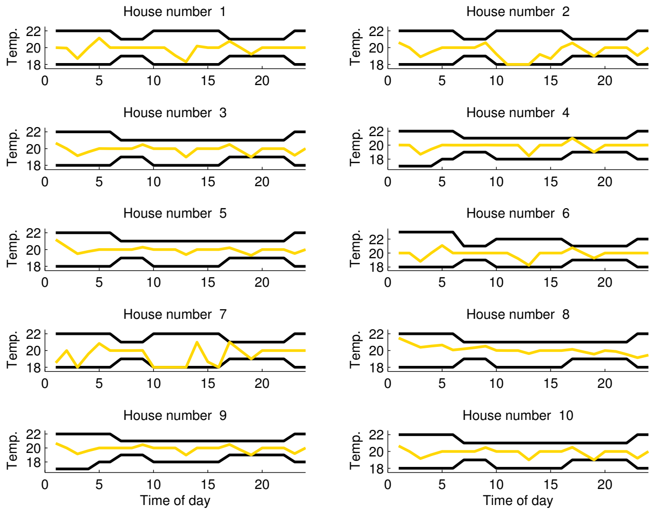

Fig. 3. Example of temperature limits and predicted temperatures using optimal power for ten houses.

Fig. 2 shows the intended power trading company user interface. Here the predicted optimized energy purchase is shown by yellow marks for every hour. The green bars on the plot indicates the flexibility for power consumption in an actual hour, e.g. in hour 8 the optimal power consumption is approx. 82 kW, the lowest possible consumption is approx. 4 kW and the possible maximum consumption is 105 kW. For comparison the energy consumption which hour by hour will keep the temperature close to 20^oC is shown in the fig 2 with red. In order to keep comfort each indoor temperature must be between an upper and lower bound as shown in figure 3. The thermal parameters, the heat pumps and the comfort requirements differ from house to house meaning that the dynamic model is unique for each house. A long-range goal is to enhance the number of remote controlled heat pump equipped houses to thousands therefore an automatic model identification method is required. Another problem is prediction of necessary power for the heated water system.

In order to move consumption to times where energy prices are low the trading company needs a tool to optimize the purchase in consideration of the comfort of the consumer. The following is presented for purchase on the spot marked. It should be noticed that the spot market is a day ahead market where participants bid 12 hours in advance their full 24 hour power profiles. In order to produce optimal bids estimates for the consumption of the individual houses are necessary. These consumptions depend on the comfort level required for the individual house.

III. Ground heat pump description and installation

The vision for the IFIV project is to make a virtual power plant that includes a great number of ground heat pump heated houses. This implies that many types of houses are in the virtual power plant, they differ with respect to isolation, varying living spaces, thickness of concrete floors, number of radiators, window areas, accumulation tank, heated water tank etc. To cover the large variety of houses simple models with adjustable parameters are preferred.

The installed heat pumps are of different brand and have different measure and control possibilities. Some heat pumps are set-point adjustable, some have on-off control, some need a minimum time between on-cycles. Other differences are the coupling of heated water tanks, some have co-current heat exchangers and some have accumulations tanks. Furthermore different brand uses different sensors.

A control box, see fig. 1, is developed for the IFIV project. The main purpose of this box is to establish communication between the heat pump and a communication server using the internet. The control box is used for data acquisition from the heat pump and auxiliary sensors and is able to activate the heat pump in a proper manner.

The IFIV project is a demonstration project where 10 private residences are selected to represent a majority of typical Danish houses. At the moment only a few installations are completed and the results in this paper is based on these.

Fig 4 is a photo of one of the installations showing the heat pump and ground/floor tubes.

Fig. 4. Typical heat pump installation from the IFIV project.

A typical sequence from one house in a 10 weeks period is shown in figure 5 and figure 6. The heat pump in question has two positions on and off. In order to see the mean power from the heat pump a filtered version is seen in the lower part of figure 5.

The data are acquired with a sampling interval of 5 minutes. The ten week period is in the spring/summer period, and the outdoor temperature is going from below the freezing point to above 25 ^oC, on the graph the diurnal variations may be seen.

IV. Model and observer based identification

The aim of a dynamic model of the room temperature is to make it possible to predict the amount of power necessary to keep the room temperature within an upper and a lower bound in order to avoid residential discomfort. The model should calculate the room temperature as a function of solar

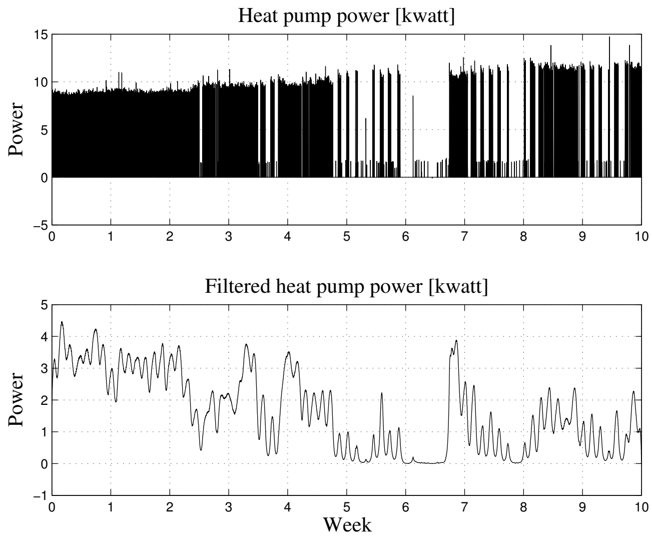

Fig. 5. Measured heat pump power, lower figure is the filtered power

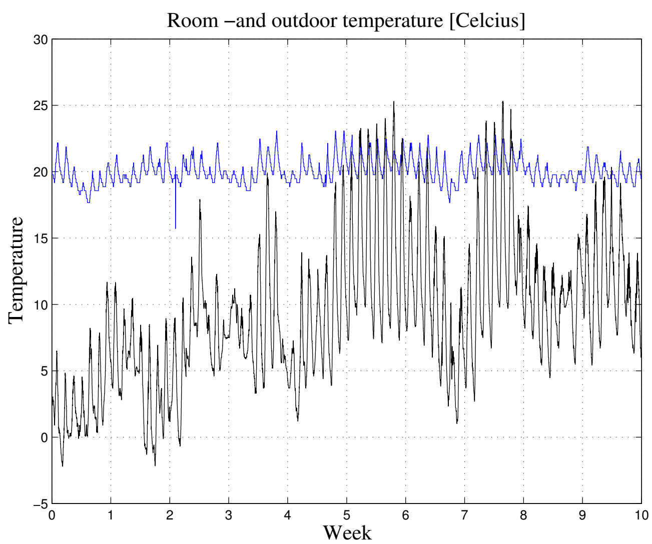

Fig. 6. Room and outdoor temperature in a ten week period.

power, the outdoor temperature and the power from the heat pump. Identification of the model parameters is limited by a low number of transducers. Furthermore not measured additional power from other sources such as wood stoves, electrical equipment, people etc. must be taken into account.

A lumped parameter model using first principles and a low number of control volumes including the essential energy stores in the building is preferred. In general a lumped parameter model based on energy balances may be written for the i'th control volume as

$$M_i c_i \frac{dT_i}{dt} = \sum_{j=1}^{N} \Big(- UA_{ij}(T_i - T_j) \Big) - UA_{ia}(T_i - T_a) + \kappa w_{sun} + w_{add} + w_{fh} \tag{5}$$

where T_i is the temperature in the i'th control volume, T_j is the temperature in the j'th control volume, w_{sun} is the solar power, w_{add} is additional power and w_{fh} is power from the heat pump to the floor. $M_i c_i$ is the heat capacity, normally a constant. UA_{ij} is the heat transfer coefficient between control volume i and control volume j. UA_{ia} is the heat transfer coefficient between control volume i and the ambient, this may be dependent on the wind speed and direction. κ is the fraction of solar power that enters the control volume e.g. through the windows, this may be dependent of the time and date.

Since there only is a limited number of measurement points and because the measurements are made in a closed loop a simple first order model is preferred. Stochastic noise is assumed to influence the states and the output. Furthermore it is assumed that the added heat can be described by a first order equation as in (7)

$$\frac{dT}{dt} = \frac{1}{CM}\Big(- UA(T - T_a) + w_{add} + w_{fh} \Big) + \vartheta \tag{6}$$

$$\frac{dw_{add}}{dt} = -\frac{1}{\tau_{add}} w_{add} + \upsilon \tag{7}$$

$$T_{me} = T + \nu \tag{8}$$

where $T_{me}(t)$ are measured data. In this model the following are unknown CM, UA, ϑ, υ, ν, and τ_{add}. To minimize the number of parameters to be estimated the variance of the three noise elements $(\vartheta, \upsilon, \nu)$ as well as τ_{add} have been kept constant in the estimation and have been chosen using physical insight.

A prediction model based on the above equations using a Kalman filter is

$$\frac{d\hat{T}}{dt} = \frac{1}{CM}\Big(- UA(\hat{T} - T_a) + w_{add} + w_{fh} \Big) \tag{9}$$

$$+K_1(T_{me} - \hat{T}) \tag{10}$$

$$\frac{d\hat{w}_{add}}{dt} = -\frac{1}{\tau_{add}} \hat{w}_{add} + K_2(T_{me} - \hat{T}) \tag{11}$$

The Kalman gain $[K_1 K_2]^T$ is determined using rough estimates of the noise properties. This includes the variance of the indoor temperature which is considered to be low and in the same range as the quantization, $0.3^o C$. A low value of the variance of the process noise υ has been applied corresponding to the assumption that the sources for added heat like wood stoves, electric ovens etc. will give slow variation of w_{add}. The last noise term ϑ represents the effect of heat pulses added directly to energy stored in the building and is chosen to give variations in the same range as the sample to sample temperature change induces by υ.

Using the above Kalman filter model with constant variances of $(\vartheta, \upsilon, \nu)$ and τ_{add} a minimization is performed in order to determine optimal values of CM^* and UA^* of the parameters.

$$[CM^* UA^*] = \underset{CM,UA}{\arg\min} \left(\sum_{t=0}^{N} (\hat{T}(t) - T_{me}(t))^2 \right) \tag{12}$$

$\hat{T}(t)$ is output from the discrete version of the Kalman model, N number of data. In the minimization $T_{me}(t)$ and $w_{fh}(t)$ are measured with 5 minutes sampling interval.

In each iteration in the minimization new values of the Kalman gains K_1, K_2 are obtained using the current parameters CM, UA and the fixed values of the noise variances.

In the observer based identification method different choices of variances of $(\vartheta, \upsilon, \nu)$ and the value of τ_{add} will give different models. Base on measurements from 6 houses values of the variances have been chosen. The value of τ_{add} has been fixed to a large value compared to the length of the data sequences.

The total heat pump power w_{hp} is the sum of the above calculated floor power w_{fh} and the power to the heated water w_{hw}. In the summer the heated water power is a substantial part of the total power consumption. The heated water flow and temperature are measured every five minutes. The distribution of the heated water consumption is not equal but concentrated in some hours mainly in the morning and in the evening, see figure 7. This statistical information is the base for a heated water model.

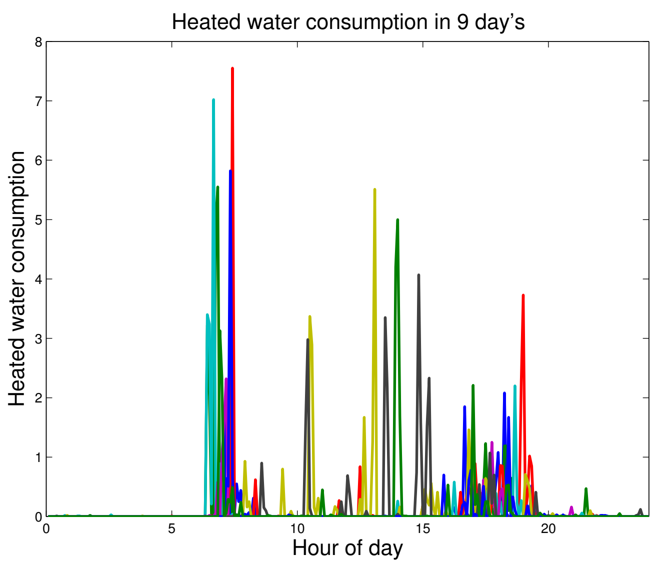

Fig. 7. The heated water consumption in 9 day's.

The identification is intended to be carried out approximately every week. To minimize the discomfort of the inhabitants of the house the identification is performed in a closed loop environment keeping the room temperature determined by the internal PI-controller. Identification in a closed loop may be problematic if the model contains too many parameters. As the house is modelled by only two parameters and the controller is of PI-type this problem is considered minimal.

It should be noticed that in a linear system vocabulary $\frac{CM}{UA}$ is the time constant and $\frac{1}{UA}$ is the gain both physically interpretable.

V. Measurements and identification results

The intended use of the identified models is to estimate the energy consumption for short and a long time interval for a single house. The long time interval is mainly used for planning an optimal hour by hour purchase of electricity, and the short time interval is used to control the power actually used in the house.

Two different tests are made, one where the time constants and gains are determined and compared week by week. In the other test a model with parameters identified using data from the preceding two weeks is used to predict house temperatures over two days using measured outdoor temperatures and measured power as inputs. The result is compared to house measurements.

It is assumed that the house parameters CM and UA are nearly constant. In the first test the identification algorithm is used in ten succeeding weeks in the spring in order to check if the identified house parameters are constant. In each week the time constant and gain are determined. Because the houses are inhabited it was not allowed to make open loop experiments such as step responses on the power, instead closed loop identification as mentioned in the previous was performed. To validate the results the ten week results are compared. On figure 8 the time constant calculated using data from one week in ten succeeding weeks is seen. The time constant is identified to a value near 20 hours, and it is seen that in spite of additional heat input (the house has a wood stove and nearly half of the power is expected to come from this) the value if not differing much from week to week. The identified gains in figure 9 are deviating in week 6 and 8. This deviation may be explained by the outdoor temperature exceeding the indoor temperature as seen in figure 6.

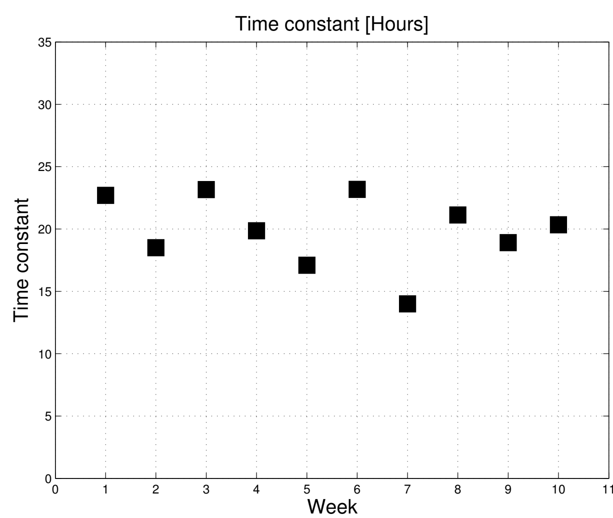

Fig. 8. Time constants for one house identified every week in a ten week period

In the second test the house model parameters and the added power are identified based on a two week measurement time sloth. The identified parameter and the added power is used in a simulation where the inputs are the measured power and the outdoor temperature from the house under test. The room temperature is simulated in two days and compared to the measured room temperature.

On both figures 10 and 11 it is seen that the level of measured and predicted room temperatures approximately

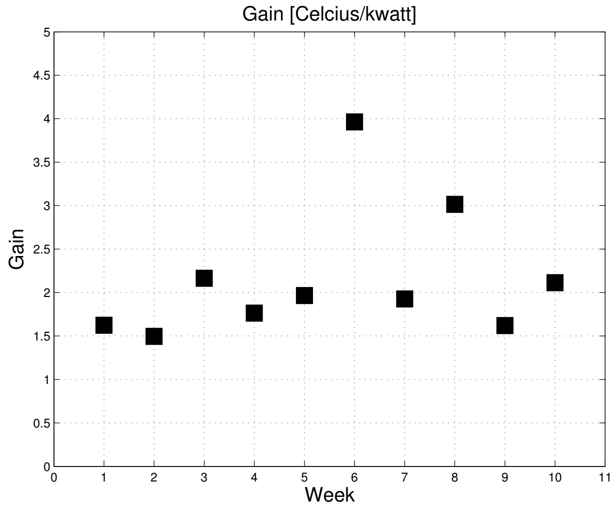

Fig. 9. Gains for one house identified every week in a ten week period

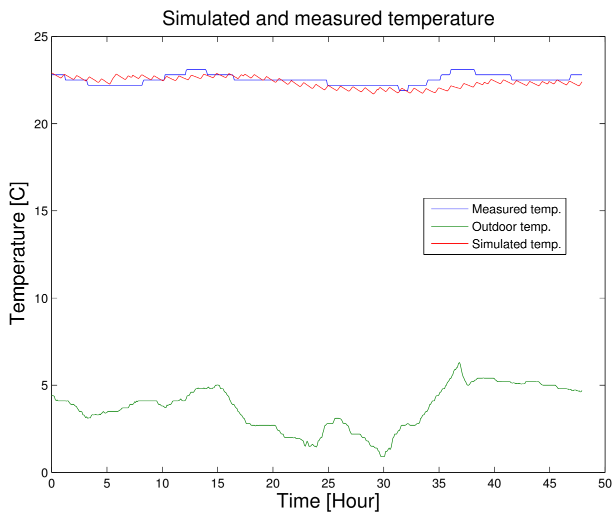

Fig. 10. Simulated and measured room temperature in a 48 hours period, 10-12 Nov., 2011

are the same, meaning that the steady state part of the model may be used for prediction of consumption for bidding in the power markets. The dynamic part of the model output reveals that not all of the variations can be explained by the measured inputs. A more detailed investigation might show whether it is possible to find patterns in the added heat which could give better predictions.

VI. Conclusion

Floor heating systems using heat pumps can help to balance production and consumption of electric energy, by moving purchase of electric energy to hours with large production without loss of comfort. To use the floor heating systems in the balancing the grid a dynamic model of the individual houses is necessary to predict the future energy demand in order to keep the room temperature within defined bounds. An observer based two state model is proposed. The two states are the room temperature and the added heat.

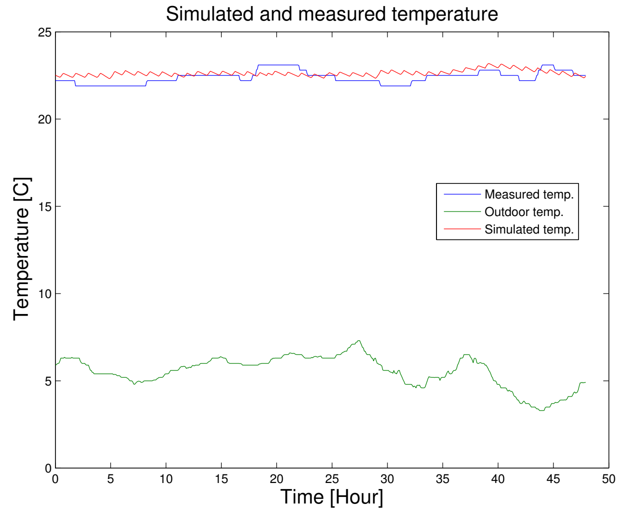

Fig. 11. Simulated and measured room temperature in a 48 hours period, 24-26 Nov., 2011

The parameters are the heat capacity and the heat transfer coefficient. These as well as the added heat is identified. Two tests are performed both showing acceptable results.

In the IFIV project the next step is to use the model for more than the mentioned houses and to investigate the potential in using the heats pumps as a virtual power plant.

VII. Acknowledgments

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