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Contribution of Domestic Heating Systems to Smart Grid Control

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***Abstract*— How and to what extent, domestic heating systems can be helpful in regaining power balance in a smart grid, is the question to be answered in this paper. Our case study is an under-floor heating system supplied with a geothermal heat pump which is driven by electrical power from the grid. The idea is to deviate power consumption of the heat pump from its optimal value, in order to compensate power imbalances in the grid. Heating systems could be forced to consume energy, i.e. storing it in heat buffers when there is a power surplus in the grid; and be prevented from using power, in case of power shortage. We have investigated how much power imbalance could be compensated, provided that a certain, yet user adjustable, level of residents' thermal comfort is satisfied. It is shown that the large heat capacity of the concrete floor alleviates undesired temperature fluctuations. Therefore, incorporating it as an efficient heat buffer is a viable remedy for smart grid temporary imbalances.**

I. Introduction

Unprecedented advances in communication technologies have created vision for large scale and very complex interconnected systems. It has also heated the control community in many aspects. Smart Grid, with a large number of electrical power producers and consumers of various types is a state of the art example of such gigantic systems. It is an Intelligent power system that can integrate all connected users' behavior and actions, all those that produce electricity, those who consume electricity, and those who do both, to effectively deliver a sustainable, economical and safe energy [1].

The presence of so many producers and consumers in interconnected sectors makes them prone to power imbalances. At the same time, it provides a chance to compensate irregularities by modifying individual power requirements of some consumers which can use power in a flexible pattern.

Electrically driven domestic heating systems form a class of such smart grid loads. Here, we are specifically interested in geothermal heat pumps which act like refrigerators in reverse and can generate up to 3-4 kWh of heat from 1 kWh of electricity. They transfer heat energy from the underground soil to residential buildings via a network of pipes. See Fig. 1. There are typically two hydronic and one refrigerant circuits interconnected through two heat exchangers. These are: 1) the underground buried brine-filled – mixture of water and anti-freeze – pipes with a small circulating pump; 2) the refrigerant-filled circuit, equipped with an expansion valve and driven by a compressor which is called heat pump; and 3) the indoor under-surface grid of pipes with another small circulating pump which distributes heat to the concrete floor of the building.

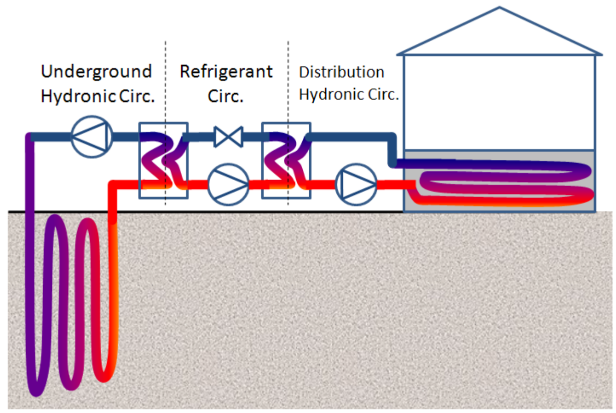

Fig. 1. Under-floor heating system with a geothermal heat pump

The underground temperature is fairly constant during several days and slowly varies with an annual pattern. This is due to the huge heat capacity of the ground. The heat is transferred from this heat buffer to the surface, into floor concrete, when needed. Why not using the same idea in a system that has a different time scale? The concrete floor could be used as a huge electrical energy buffer, to be stored in form of heat, when there is a power excess in the grid. On the contrary, when there is a power shortage, no or a little power should be drawn from the grid into the heating system. This can also be embedded in electricity pricing policies.

From residents perspective, they can avoid high electricity bills by deferring their daily power consumption. According to [1], approximately half of the economic potential for saving in annual electricity bills, can be achieved by postponing power consumption in each day.

This paper studies another perspective of the problem, i.e. maintaining electrical power balance of the grid. It investigates how much power imbalance could be compensated without sacrificing residents' thermal comfort which is the primary objective of heating systems. The idea of utilizing flexible loads to regain balance in a smart grid is not novel. It is also known that hydro and pumped devices are the most typical type of storage devices which can turn electrical power into heat to be stored in previously installed infrastructure [2]. However, we are going to incorporate concrete floor instead of a hot water reservoir. Moreover, this research is motivated by the fact that heating systems are used almost year around in countries like Denmark and could be thought of as an invariable part of the grid. These potential compensators could be numerous, as many as houses, and distributed geographically. Therefore, it is of importance

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and value, if the amount of possible compensating action is quantified. This is the task that we have accomplished and verified in this paper via simulations with real parameters.

As the first detailed step, our control strategy for the heating system for a specific apartment is given in Section II. Presentation of the results start in Section III by reconstructing a typical scenario of power setpoint tracking. It is assumed that the power providing company, suggests a setpoint profile for power consumption of the heat pump. This section is concluded by generalizing the sample simulation to the extreme cases to see how much, and for how long, power imbalances can be compensated by employing the above mentioned method. This helps the power providing company to produce a feasible setpoint profile. Section IV concludes the paper by offering a discussion on future works.

II. Strategy of Control

Our case study is a 54 m^2 apartment which consists of three separate heat zones, i.e. rooms, shown in Fig. 2.

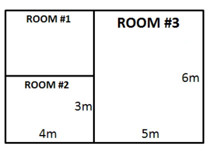

Fig. 2. Sketch of the apartment with three separate heat zones

There are a large number of parameters taken into account in our simulations which we do not mean to list in the main body of the paper. An introduction to the model and the parameter values are given as an appendix instead. It is, though, worth saying that the chosen values for all parameters are in accordance with the typical experimental and standard values.

Each room in Fig. 2 has a separate grid of under-surface floor heating pipes. As a whole, they form the hydronic distribution circuit of the apartment. The flow of heating water in each room is controlled by a valve. The valve opening is adjustable and is controlled by a local PI controller such that the room-specific temperature setpoint is followed in presence of exogenous disturbances.

The circulation pump in the distribution circuit is controlled that to regulate the differential pressure across all three parallel branches of the rooms' pipe grids. Thus, the flow through each valve only varies by its opening position.

As of the refrigerant circuit, the expansion valve has a built-in mechanical feedback mechanism to marginally prevent flow of condensed refrigerant into the compressor, i.e. the heat pump. The heat pump could be continuously controlled. In one of our recent works [3], we have employed a Model Predictive Controller (MPC) to reduce heat pump's power consumption as much as possible. It is achieved when the *forward temperature* has its minimum allowable value, described as follows. Forward temperature is the temperature of water at inlet of the distribution piping grid; and it should be high enough in order to facilitate room temperature control by local PI controllers without pushing any of the valves into fully-open saturated status, otherwise no actuation capacity is left for compensating exogenous disturbances.

Nonetheless, in this research, we are going to drive the heat pump, by directly exploiting the power consumption setpoint that is prescribed by the power providing company. Therefore, no specific control algorithm is required for the heat pump. The only constraint to satisfy is to restrict the highest permissible forward temperature which is hardly reachable in practice, as well.

In case of power surplus, forward temperature is increased which will eventually result in lessening rooms' valves openings. In order to let heat be stored in the concrete as much as possible, temperature setpoint of the rooms should be increased by a certain amount, defined as *thermal tolerance* (TT) level. TT is user adjustable in the interval TT $\in [TT_{min}, TT_{Max}]$. However, this does not guarantee that the room temperature remains bounded by its original setpoint plus TT.

In case of lack of power, no room temperature setpoint modification is required.

The above mentioned strategy is very simple to implement and clearly not optimal in terms of energy efficiency of the individual heating system. However, it facilitates integration of the domestic heating into the power grid control system.

III. Case Study Results

A. A simple Scenario

Fig. 3 shows a typical power setpoint tracking scenario, with power setpoint profile depicted in the first graph. Initial steady state value of 263 W is associated with forward temperature 36.6°C. The outdoor temperature is assumed to be 0°C. Periods of power excess/shortage are assumed to be one hour long with 30 min power surplus of as 50% much as the initial power, followed by 30 min lack of power of the same amount. Thus, the average power consumption is kept unaltered.

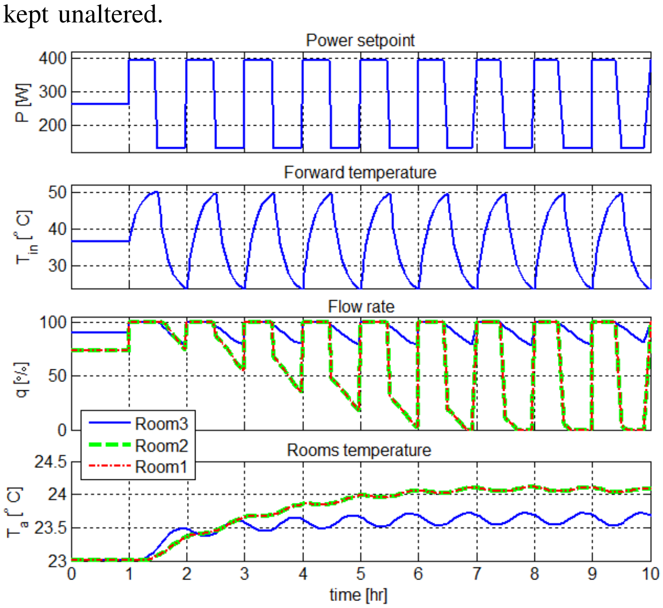

Fig. 3. A typical power setpoint tracking scenario. 50% power surplus and shortage with duration of half an hour is tolerated by the system, provided that the thermal tolerance level of rooms are set to $+2°C$.

The third graph in Fig. 3 shows water flow percentage through distribution pipes of individual rooms. At steady state, control valve of room 3 is at 90% flow capacity to follow the temperature setpoint 23°C, when no exogenous disturbances are present. For rooms 1 and 2, 74% of flow range is adequate to reach the desired temperature. The temperature setpoint is assumed to be equal in all three rooms. At $t = 1$ hr, power consumption of the compressor increases. It takes some time for the forward temperature to rise, but all three valves become fully open instantly due to modification of rooms' temperature setpoints to 25°C, corresponding to a thermal tolerance level of 2°C surplus. Note that the user's desired temperature is still 23°C and this setpoint modification is merely in order to facilitate transfer of heat energy into the concrete floor.

At steady state, after approximately 10 hours, i.e. 10 surplus/shortage intervals, it is shown that the valves of rooms 1 and 2 function like on-off devices, keeping room temperatures about 1°C higher than the original setpoint. Average temperature in room 3 is even closer to the original setpoint, but with more noticeable fluctuations. This behavior strongly depends on PI controllers selected parameters.

This simulation shows that the deviation of rooms' temperature due to a specific power setpoint profile were bounded in the permissible user-defined region. This was the consequence of applying an appropriate power setpoint profile, called *feasible* setpoint profile henceforth, combined with the corresponding suitable choice of thermal tolerance level. The power providing company could establish pricing policies to encourage users to set their thermal tolerance level at high values. Then the company can issue a feasible power setpoint profile pursuant to the user's own choice.

B. Generalized Results

The next question to be answered is how to prescribe a feasible power setpoint profile based on each user's thermal tolerance level. Fig. 4 shows a chart that can be used to predict what kind of pulses in the power setpoint profile can be accommodated by the heat pump without disrupting resident's thermal comfort, which means:

$$T_{r_i} \in [T_{r_i Ref} \pm TT], \qquad \forall i = 1, 2, 3 \tag{1}$$

in which T_r stands for room temperature, and T_{rRef} indicates its setpoint. Index i refers to the room number.

As an example, Fig. 4 shows that a power surplus pulse with an amplitude of 350 W and a duration of 1 hour can be marginally accommodated by the heat storage of a 54 m^2 flat, if the temperature tolerance is set to 0.5°C. If either the amplitude or the duration is less, the excess of electrical power can be stored as heat without any difficulty. It is worth saying that the given chart in Fig. 4 is dependent on the following parameters:

- Ambient temperature which is assumed to be 0°C
- Local PI controller parameters

Moreover, when a different temperature setpoint is chosen for each room, the nominal heat pump power would be different, i.e. different from 263 W in this case. Thus, the chart should be shifted along the Y-axis accordingly.

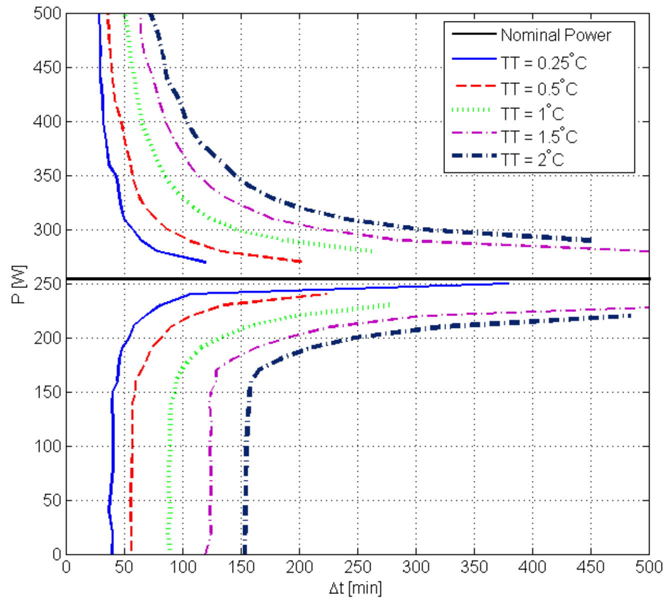

Fig. 4. Power setpoint generation assistant chart for a 54 m^2 flat, containing several thermal tolerance (TT) levels

IV. Disscusion and Future Works

This paper serves as a proof of concept. The most common power imbalance pulses in power systems last for less than half an hour, and are as large as ±50% nominal value. Our results show that, these imbalances can be well accommodated even by a small 54 m^2 apartment with a tightly selected thermal comfort level of 0.25°C in a mild cold weather with a commonplace desired indoor temperature.

Throughout the paper, we have assumed that the power setpoint profile is provided by the power grid at any time instant. This assumption requires a tremendous amount of information to be transferred by the power providing company to all users. A more practical approach is to consider an intermittent communication between the grid controller and the user at equal time intervals. At the beginning of each interval, the grid controller send a message asking the user to try to increase/decrease its power consumption by $\pm\Delta P$. As a result, the burden of computing power setpoint profile is put on heat pump control system which its design is not trivial anymore. An ongoing optimizing mechanism should be exploited which suggests a MPC design. The MPC controller objective is to define the power setpoint in order to satisfy demands of the grid control system, subject to several constraints, which are: 1) avoid valve saturation when the room temperature is not higher than its setpoint; 2) avoid too high forward temperature in order to keep the heating system from damage; and 3) maintain the room temperature in the interval defined by (1) . It is worth saying that, the demand of the power providing company may not be completely satisfied due to probable conflicts with the above constraints.

Design of such a MPC controller makes use of the chart in Fig. 4 and is amongst our recent future works.

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APPENDIX

This amendment is devoted to modeling details of the components and subsystems which are employed in our simulations. All of the used symbols and subscripts henceforth, are listed in table I.

TABLE I
SYMBOLS AND SUBSCRIPTS

Nomenclature	
A	surface area (m^2)
C	thermal capacitance $(J/kg\,°\mathrm{C})$
K	equivalent heat transfer coefficient of pipes and concrete
P_c	consumed power by compressor
P_t	transferred power to the house
Q	heat (W)
q	water flow rate in floor heating (kg/sec)
T	temperature $(°\mathrm{C})$
U	thermal transmittance $(W/m^2\,°\mathrm{C})$
τ	time constant
Subscripts	
amb	ambient
e	envelop
f	floor (with 1 and 2 indices corresponding to the first and second layer of concrete floor)
FH	floor heating
i	room number
in	forward water into floor heating system
n	n^{th} lump section of the floor heating pipe
out	return water from floor heating system
r	room
ref	reference
w	water

A. Zone Model

Energy balance equations of each single room are derived based on the analogy between thermal systems and electrical circuits mainly based on [4]. Fig. 5 shows a schematic view of the room with its analogous electrical circuit. Energy balance equations at the envelop, floor, and air nodes are as follows:

$$\begin{aligned}
C_e\dot{T}_e &= U_eA_e(T_{amb}-T_e)+U_eA_e(T_r-T_e) \qquad (2)\\
C_{f_1}\dot{T}_{f_1} &= U_{f_2}A_f(T_{f_2}-T_{f_1})+U_{f_1}A_f(T_r-T_{f_1})\\
C_{f_2}\dot{T}_{f_2} &= U_{f_2}A_f(T_{f_1}-T_{f_2})+Q_{FH}\\
C_r\dot{T}_r &= U_eA_e(T_e-T_r)+U_{f_1}A_f(T_{f_1}-T_r)
\end{aligned}$$

in which T_e represents the envelop temperature, T_{f_1} and T_{f_2} are the concrete floor's first layer and second layer temperatures, respectively; and T_r represents room temperature. Exogenous inputs include ambient temperature T_{amb}, and heat from floor heating Q_{FH}.

Envelops, room air and each layer of concrete floor are assumed to be at uniform temperature, i.e. no temperature gradient is considered in any of them. Heat flux via partition walls between the rooms is neglected, provided that temperature differences among the rooms are not noticeable.

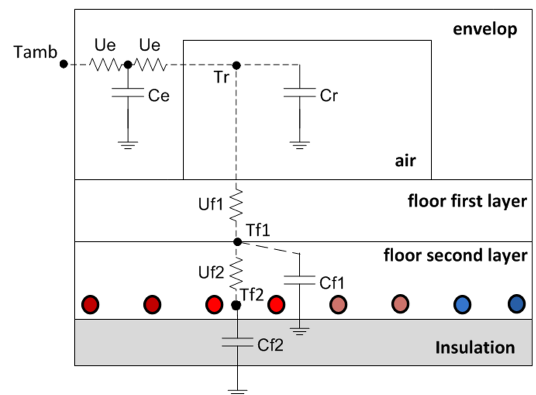

Fig. 5. Analogous electrical circuit to the room thermal model

B. Hydronic Floor Heating

The considered floor heating has a serpentine piping with the pipes embedded into a heavy concrete as shown in Fig. 5. As a typical assumption, water flow is limited to a specific rate by balancing the total opening of the pipes. To guarantee the highest possible floor heating efficiency, the diameter of the pipes is adjusted at the point of branching from manifold. Since the distribution circulating pump provides a constant differential pressure across the valves, maximum flow rate would be limited by such a balancing task.

Floor heating is modeled as distributed lumped elements governed by:

$$C_n\dot{T}_n = c_wq(T_{n-1}-T_n)+K_n(T_{f_2}-T_n) \qquad (3)$$

with T_n as the nth section temperature. Distribution of lumped elements are considered to be along the pipe. Heat propagation from the pipes exterior surface is considered to be only upwards toward the floor surface. We have also assumed that heat is transferred between two sections only by mass transport, implying that convective heat transfer is neglected. Another assumption is that the pipes material and water are at the same temperature. Neglecting the thermal resistance of the pipe, heat transfer coefficient, K

would only depend on thermal conductivity of concrete, i.e. $K_n = U_{f_2} A_n$ in which A_n is the effective area of the nth section. U values are selected based on thickness and composition of concrete floor layers, [5].

Heat transferred to the second layer of concrete floor is computed as:

$$Q_{FH} = \sum_{n=1}^{N} K_n (T_n - T_{f_2}) \tag{4}$$

The employed simulation model for floor heating is inspired by a similar radiator model addressed in [6]. The distributed lump model is derived based on the analogy to floor heating, proposed in [7].

C. Geothermal Heat Pump

Heat pump is a device which applies external work to extract heat from a cold reservoir and deliver it to a hot reservoir. Three separate fluid circuits are required for a heat pump to retrieve heat energy from heat source and transfer it to the heating system of a house. These circuits are already shown in Fig. 1.

Two heat exchangers are exploited in these circuits. Coefficient of performance (COP) is defined for the refrigerant circuit and two adjacent heat exchangers. It indicates the relationship between the amount of produced heat and consumed electricity by the heat pump. COP has a strong positive correlation with differential temperature between the influent brine of the primary heat exchanger and the influent water of the house. Given a constant brine temperature, COP is determined by referring to the manual of the heating system vendor.

Given COP value, the consumed power by the compressor in the refrigerant circuit (primary side) can be described as:

$$P_c = \frac{P_t}{COP} \tag{5}$$

in which P_t is the transferred heat to the secondary side, i.e. house and P_c is the consumed power by the compressor.

Conventional heat pump control takes action based on outdoor temperature. Forward water temperature setpoint is determined based on the ambient temperature, which can be regarded as a feedforward control approach. A PI controller adjusts the absorbed power by the compressor in order to maintain the target forward temperature. Normally, it takes a few minutes for the heat pump to reach the new forward temperature.

In the present study, however, compressor is driven by the power setpoint profile provided by the power company. Hence, to find the forward temperature corresponding to a specific P_c we have utilized (5). Both P_t and COP are functions of the forward temperature T_{in}. P_t can be described as energy loss of the building:

$$P_t = c_w q (T_{in} - T_{out}) \tag{6}$$

with T_{out} as return water temperature. In an efficiently balanced floor heating system, as implied before, the return temperature would always be 1 to 2°C higher than room temperature. Hence, it can be regarded as constant being at a specific room temperature, i.e. 23°C in simulations. In this case $T_{out} = 25°C$.

COP of a specific heat pump is borrowed from the manufacturer's datasheet and is shown as data points in Fig. 6.

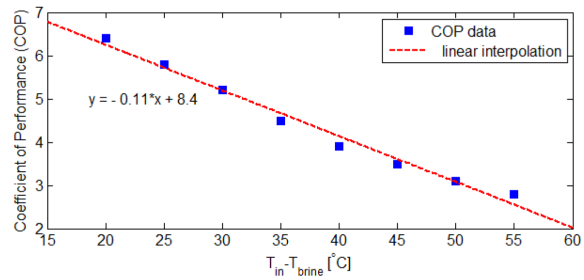

Fig. 6. COP against temperature difference between forward and brine water

An interpolating line is fitted to the points. The linear approximation is used to find T_{in} corresponding to the compressor consumed power. Therefore, (5) turnes into:

$$P_c = \frac{c_w q (T_{in} - T_{out})}{a T_{in} + b} \tag{7}$$

with a and b as constants of the approximated affine map in Fig. 6. At a specific T_{out} and P_c, forward temperature can be found with no difficulty based on (7). Calling this temperature T_{inRef}, it takes a few minutes for the heat pump to transfer heat to the secondary side and maintain this temperature:

$$\frac{T_{in}}{T_{inRef}}(s) = \frac{1}{1 + \tau s} \tag{8}$$

To summarize this section:

- room dynamics, i.e. the dynamics between room temperature and temperature of the envelop, ambient, and floor, are governed by (2)
- floor heating dynamics, i.e. the dynamics between concrete temperature and forward temperature, are governed by (3)
- heat pump dynamics, i.e. the dynamics between forward temperature and consumed electrical power, are governed by (7) and (8). Note that, (7) is used to find T_{inRef}.