SIMULTANEOUS IMBALANCE REDUCTION AND PEAK SHAVING USING A FIELD OPERATIONAL VIRTUAL POWER PLANT WITH HEAT PUMPS

Olaf van PRUISSEN
TNO – The Netherlands
olaf.vanpruissen@tno.nl

Koen KOK
TNO – The Netherlands
koen.kok@tno.nl

Aldo EISMA
TNO – The Netherlands
aldo_eisma@nl.ibm.com

ABSTRACT

The Dutch electricity infrastructure is challenged by the deployment of large numbers of heat pumps in newly-built domestic residences. An example is the apartment complex of Couperus in The Hague where 300 apartments are heated by individual heat pumps. This building was operated as a Virtual Power Plant for ten months. Using the PowerMatcher as a coordination mechanism, the VPP balanced a near-by wind farm providing a peak-shaving service to the local distribution station. Flexibility was provided by shifting the operation of the heat pumps in time, which is dependent on a certain bandwidth in the indoor temperature in the households. In this way up to 21% of the power drawn by the heat pumps was made flexible without infringing user comfort. Using this flexibility, 94% of the wind farm imbalance was reduced. Further, the system successfully performed peak-load reduction at the LV-to-MV substation simultaneously to the VPP operation. During the test indoor temperatures and the status of the heat pumps were recorded to secure user comfort. The Couperus project is one of a few smart grid demonstrators that did not include friendly users only, as all occupants in the apartment building were included in the demo. Therefore, the operational temperature bandwidth was set to a conservative value of 0.4 °C to avoid any loss of comfort. As a result, no complaints of the inhabitants with respect to the temperature were reported.

INTRODUCTION

The Dutch electricity infrastructure is challenged by the deployment of large numbers of heat pumps (HP) in newly-built domestic residences. The introduction of heat pumps is an important step towards a more energy efficient built environment [1,2] . However, large scale introduction of heat pumps poses a challenge for distribution grid operators in terms of thermal and voltage limits of LV networks [3]. In areas such as The Netherlands, where homes and buildings are predominantly heated using natural gas, this impact is even higher. Heat pumps consume in comparison to other devices in Dutch households more power. On cold days heat is demanded simultaneously and heat pumps can switch on simultaneously and a heavier load on the grid can occur than usually. This can either be prevented by using thicker cables and larger substations or by controlling the switching on/off behaviour of the heat pumps so that no overload occurs. To cope with these challenges, the use of smart strategies using the flexibility potential of these loads has been advocated [4, 5]. At the same time, this flexibility can be used to optimise the trading position of the energy supplier involved, e.g. by reducing the imbalance of a wind farm, i.e. the difference between the day-ahead forecast and the actual production. This paper describes a Virtual Power Plant (VPP) aggregating the heat pumps of 300 apartments in a single building. The VPP both performs imbalance reduction and capacity management (peak shaving) on the local LV-to-MV substation.

FIELD TEST SITE

This study describes the results of a field test during 10 months in an apartment complex with 300 apartments in one well insulated building block in Couperus, The Hague in The Netherlands. The apartments are individually heated by heat pumps manufactured by ITHO Daalderop with an input power of 1 kW. The heating is for the purpose of room heating by floor heating and domestic hot water by using a boiler as a storage for hot water. All heat pumps are connected to a small number of aquifers where the temperature of the ground water is 11-12°C. It gives the opportunity to heat with a rather large energy efficiency with a Coefficient of Performance (COP) of about 4. Due to a day-night tariff tap water heating preferably occurs in the evening after 23 hrs, thus lowering the electricity bill for the users. Communication between the heat pumps and the server with the database installed and running the agents is performed using a RF system already in operation by ITHO Daalderop. This system was normally used for fault detection of the heat pumps. During the installation and testing the RF system appeared to have some limitations regarding the connection speed. Connecting all 300 heat pumps would take 30 minutes. It was decided after some optimization and testing that merely 150 heat pumps would be part of the VPP in order to have a reasonable response time with respect to the signals coming from the imbalance and the DSO substation concentrator agent.

AGENT INTELLIGENCE AND VPP

As a coordination mechanism for the VPP the PowerMatcher was used. A detailed description about this market based solution involving the bidding

strategies of the agents can be found in [4,5].
At the software architectural level the VPP consist of a tree like structure with an auctioneer at the top level which is connected to an objective agent representing the imbalance due to a wind farm which is called the imbalance agent. Below the auctioneer a DSO concentrator agent is connected representing a substation agent and below the substation agent all the agents are connected representing the 150 heat pumps.

Imbalance agent

The imbalance agent represents the imbalance in the market which needs to be reduced. Since at large scale introduction of renewables wind farms will contribute dominantly to the imbalances occurring, as an input for this agent the generated real-time output power of a wind farm was used. Since 150 heat pumps were connected of course only a power less than 150 kW can be reduced, so the output had to be scaled down. The retailer in this project Eneco scaled the signal down to a value of ±10 kW, which was an approximation of the power which could rather easily be reduced.
The power of interest is not the actual power generated at the wind farm, but the difference between this power and the predicted power. Eneco provided a model forecasting the wind power generation and thus this differential power $P_{diff} = P_{actual} - P_{generated}$ was input to the imbalance agent.
The bid curve of the imbalance agent is flat bid curve of which the power is equal to the imbalance, so imbalance is requested at any price. The power on the vertical axis of the bid curve is calculated by taking the difference of a moving average of P_{total} which is the total power consumption of all heat pumps in the VPP as measured during the most recent (e.g. 5) biddings and P_{diff}. Consequently when more power needs to be consumed due to less power generation at the wind farm than predicted, the price calculated by the auctioneer will be lower than without having the imbalance agent in the cluster.

DSO Substation Agent

The DSO substation concentrator agent has the duty to protect the substation from becoming overloaded. The maximum capacity P_{max} at the substation may not be exceeded. For this task the actual power at the substation P_{sub} is measured, for which the DSO Stedin was responsible. P_{sub} is continuously compared to P_{max} and when P_{sub} is less P_{max} no transformation of the price signal at the DSO concentrator agent is performed. However when P_{sub} exceeds P_{max} the price signal is transformed as described in [5] in the section describing the propagation of capacity constraints, although in a slightly adapted way taking care of the uncontrolled load.

Heat pump agent

The heat pump agent is responsible for heating the boiler for domestic hot water and room heating. The way the bid curve is constructed, was the committed to ITHO Daalderop which is the manufacturer of the heat pumps and is part of their IP. Of course the loading or heat in the boiler is an important parameter as well as the difference between the indoor temperature and the set point. The bid curve is a simple Θ function: at low prices the power in the bid curve is equal to the input power of the heat pump and above a certain price the power is 0.
The heat pumps operated at a temperature bandwidth of 0.4 °C. When this temperature is exceeded just a flat bid curve is generated, demanding power at any price, so a must run situation occurs. Once the heat pump was turned on, a minimum time of operation was forced by sending a flat bid curve as long as desired by the device.
Due to a day-night tariff tap water heating on which the bill of the inhabitants is based occurred in the evening after 23 hrs and further during the night. When the heat pumps were not controlled this was clearly visible by a high peak power measured at the DSO substation occurring immediately after 23 hrs. The bidding strategy of the heat pump was such that heating took place after 23 hrs but the willingness to pay for electricity was thus distributed over time that not all controlled heat pumps turned on immediately at 23 hrs.

RESULTS

A field test was conducted from May 2013 until March 2014. IBM was responsible for the operation of the VPP, coping with disturbances in the system and storing the data in the database. Generally the power measured at the substation was reliable though a few disturbances happened, e.g. a change in a IP-address. The power input for the imbalance agent sometimes caused identical values for a long period time or small or large spikes. Due to these disturbances duration curves representative for a month as shown in this paper have a different length.
As the apartment complex was newly built the inhabitation In the first few months all apartments were occupied
Apart from the outdoor temperature, indoor temperatures, set points and the status of the heat pumps were monitored at all apartments involved. This provided a lot of interesting information which will be published elsewhere, in this paper the focus is on the performance of the VPP. However the general observation is that in more than 90% of the apartments the indoor temperature followed the set point closely and no user complaints were registered.
First an example is discussed regarding the performance of the VPP on an arbitrary day in autumn when just imbalance reduction was requested and no peak shaving occurred. In figure 1 on November 15th in 2013 a fluctuating request for compensation by the wind imbalance agent is visible. The dashed curve shows the base demand which is the power that would be consumed

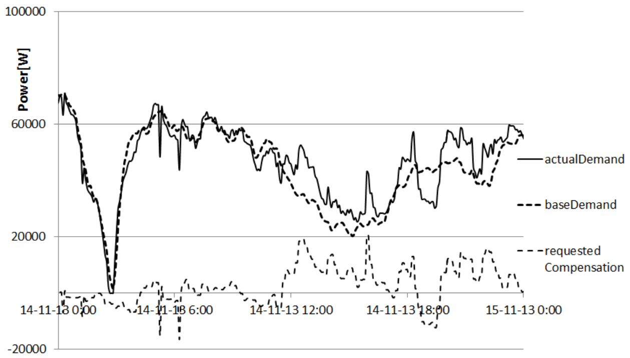

Figure 1: The base and actual power consumption of 150 heat pumps connected to the VPP and the compensation as requested by the wind imbalance agent during a day in November.

by the heat pumps if the VPP would not be controlled by the PowerMatcher at that particular time. The solid curve shows the actual demand of the heat pumps. For proper understanding it should be noted that each power in the dashed curve (basedemand) is a result from the operational modes of all heat pumps run before that time (where compensation requests could be taken into account), resulting in certain temperatures in the apartments in the VPP and the basedemand is then the power that would be consumed without any control in the VPP. At about 2:30 hrs a sudden drop occurs, this is due to a reset by the ITHO-Daalderop server which communicates with all heat pumps and which unfortunately could not be prevented during the field test. In the analysis sometimes all the data from 1:30 until 3:30 hrs were omitted.

The difference between the actual and base demand is the most interesting feature, e.g. at 12:00 hrs more power and at 18:00 hrs less power is consumed than what would be consumed without control, which corresponds to the requested compensation. This difference is in fact the actual compensation. In a next part of this paper each pair of points of the actual and the requested compensation will be used to analyse the performance of the imbalance reduction, but first in fig.2 for the same day also the maximum allowable and minimum allowable demand is shown. The minimum power demand of the VPP is determined by the heat pumps which are in a must run mode; the indoor temperature is below the minimum required set point so they have to be turned on for user comfort. The maximum demand is determined by the heat pumps which cannot be turned on because otherwise the indoor temperature would become too high. Figure 2 shows that the solid line representing the actual demand always stays within the range between the minimum and maximum demand. If the actual demand equals the minimum or maximum demand no more flexibility is available in the VPP and on such an occasion the requested compensation might not be met.

The difference between the maximum and minimum bandwidth is equal to the available flexibility within the

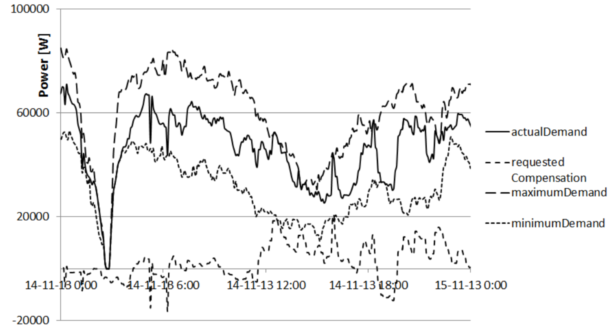

Figure 2: The maximum and minimum possible demand as requested by the heat pumps in the same period of time as in Figure 1.

VPP. As during warm days heat is just required for heating the buffers of the domestic hot water system, the heat pumps will be rather scarcely be turned on. As during cold days heat is also required for room heating, more heat pumps will turn on, so a strong dependency of the availability of flexibility on the season or outdoor temperature is expected. For several months the available flexibility was determined as shown in a load duration curve in figure 3.

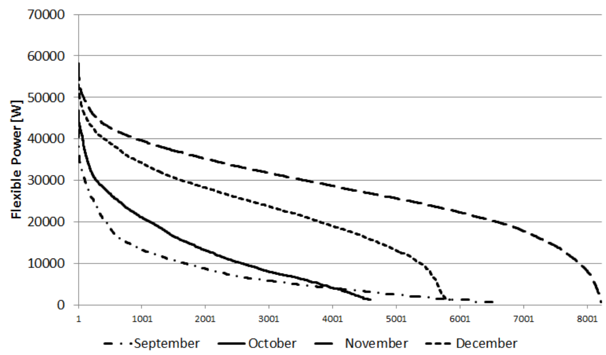

Figure 3: The load duration curve of the available flexible power in the Couperus VPP for 4 months in autumn.

From figure 3 it can be observed that the available flexibility increases from September until November, where the outdoor temperature decreases from about 15 till 5 °C. The curve drawn for December is impaired by several days with disturbances in the system where reliable values could not be recorded. The available flexibility was also determined during simultaneous imbalance reduction and peak shaving in the next three months as discussed later in this paper. The available flexibility for January, February and March is shown in figure 4.

Both figure 3 and 4 suggest that from November until March on average the same amount of flexibility is available and that the amount of flexible power is hardly influenced by the simultaneous striving for peak shaving and imbalance reduction. This is further substantiated by the average available flexible power in several months in

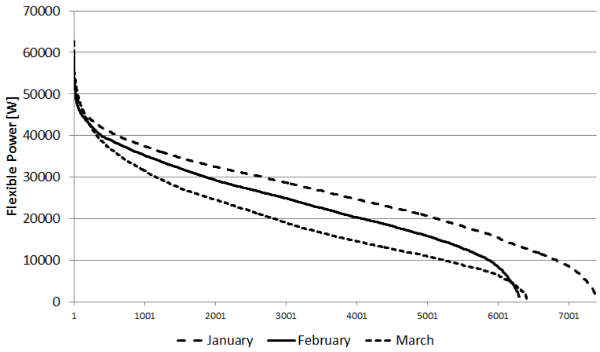

Figure 4: The load duration curve of the available flexibility in the Couperus VPP at simultaneous imbalance reduction and peak shaving in typical winter months.

table 1. The average total power of all heat pumps in the VPP is about 125-130 kW (85% of 150 heat pumps). In the months September October less flexible power is available.

As mentioned earlier from the values in fig. 1 the requested and realized compensation can be derived. The results for the first half of November are shown in fig. 5. As can be seen in almost all occasions the compensation requested can be quantitatively fulfilled: the slope is equal to 1 and the correlation between both signals is 0.90; when the measurements between 1:30 hrs and 3:00 hrs are excluded than the correlation increases even to 0.92. As a measure for the imbalance performance of the VPP the percentage of realized compensation versus requested compensation was taken and determined at 94,6%, where measurements between 1:30 hrs and 3:00 hrs were excluded.

Month	Flexible power [kW]	Performance percentage
September	7,4	91,7 %
Oktober	13,8	93,7 %
November	27,4	94,6 %
December	24,2	93,7 %
Januari	26,2	94,6 %
Februari	24,5	92,4 %
Maart	21,1	94,4 %

Table 1: The average available flexible power and the percentage of response for imbalance reduction during the months September 2013 until March 2014. From January also simultaneous peak shaving occurred.

This experiment was conducted during the complete field test and the percentage of imbalance performance and correlations was determined for all the months, although from January until March 2014 also simultaneous peak shaving occurred. The percentages are shown in the third column of table 1.

Although the available flexible power bandwidth in September is not quite high surprisingly it is enough to

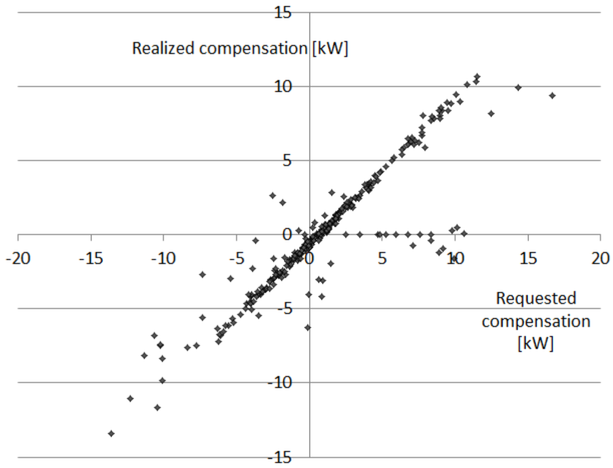

Figure 5 The relation between the requested and realized imbalance reduction in the first half of November at an average outdoor temperature of 9,5 °C with a correlation of 0.90 and a response of 94,6%.

provide an imbalance performance percentage of 92,7%, apparently the VPP is able to respond quite well to the requested compensation. It was determined that 21% of the total power of the heat pumps is flexible. This was deduced from the total power of the heat pumps being 150 kW, the number of inhabited apartments being 85% and a minimum actually reduced bandwidth of 28 kW. Based on a few assumptions, e.g. the average power of a heat pump in a household and the future penetration of heat pumps this may account for a total of flexible power of heat pumps in the Netherlands of about 0,5 GW.

Another remarkable observation from Table 1 is the rather high imbalance performance during simultaneous peak shaving.

Peak shaving

From January till March 2014 peak shaving was in operation. As still 150 heat pumps were not part of the VPP and especially at 23:00 hrs almost all those heat

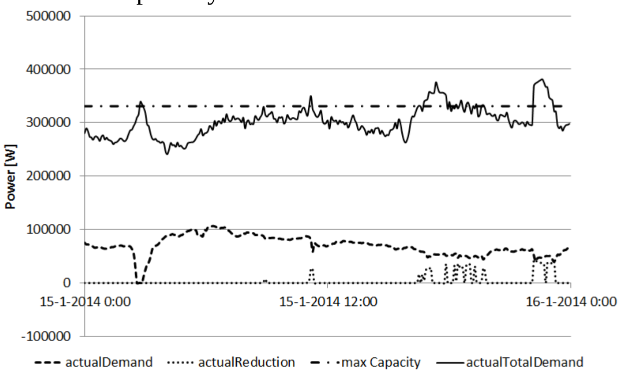

Figure 6 Peak shaving 150 of 300 heat pumps in the VPP Couperus on January 15th 2014 showing the maximum capacity of the substation, the actual total demand, the actualDemand of the heat pumps controlled and the actual reduction achieved.

pumps turned on for heating the boiler, analysis of the performance of the VPP at peak shaving is less straightforward than for imbalance reduction. As an example figure 6 shows the result of peak shaving. Figure 6 shows that on January 15th the average power of heat pumps that can be controlled is about 100 kW; the effect of the reset of the ITHO server at 1:30 hrs is also visible. The total power measured at the substation on average is near to 300 kW, of which about 100 kW is due to uncontrolled heat pumps. The maximum capacity of the substation is set to 325 kW; of course the actual maximum capacity of the substation is larger than 325 kW to prevent actual overloading and the risk of fire in the substation. During the day at three times the maximum capacity exceeds the actual total demand. However it can be seen that the actual demand of the heat pumps controlled, decreases (most notably at 12 hrs and 23 hrs) and actual reduction happens on all three occasions. This is further substantiated by the observation that (only) during the three exceedances the price in the VPP is the maximum price, in fact more than this signal for reduction is not possible in the VPP. The maximum capacity is mainly exceeded for one reason; that is the turning on of the uncontrolled heat pumps, especially at 23 hrs when the boilers for hot tap water are heated. Another factor playing a role is that the heat pumps that are in a must run mode, cannot be turned off. This can be concluded from the fact that the actual demand does not approach 0.

Controlling all 300 heat pumps will lead to indisputable conclusions regarding peak shaving. However the observation of the price reaching maximum price and peak shaving occurring only when necessary suggests that peak shaving is well established within the VPP.

CONCLUSIONS

In the Couperus project it was investigated whether the apartment complex with 300 individually heated apartments can act as a VPP. By shifting the turning on/off behaviour of the heat pumps in time it is demonstrated that flexibility is created which enables reduction of imbalance in the grid and peak shaving at the level of the low voltage grid. During the project the indoor temperature and set point of all in the field test involved apartments have been measured and hardly no deviations have been detected. No complaints of the inhabitants with respect to the temperature were reported. This is remarkable since the inhabitants cannot be described as ‘friendly users’.

In the project the supplier of the heat pumps ITHO Daalderop has chosen to operate at a temperature bandwidth of 0.4 °C to diminish the risk of loss of comfort . Given this bandwidth it is possible to use 21% of the total power of the heat pumps in Couperus for imbalance reduction during a large period of time in spring, summer and autumn. During this period of time less flexibility is available in the months of September and October than during the winter months.

For each month the availability of flexible power for imbalance reduction has been determined, and the delivered flexibility has been examined to assess the security of delivering this flexibility. As in general 94% of the requested imbalance was realized, the results suggest that in most cases the requested imbalance reduction can be fulfilled. No points of improvement of the functioning of the imbalance agent can be discerned.

Peak shaving has been demonstrated. It has been demonstrated to accomplish peak shaving together with imbalance reduction. Thus the dual goal objective is realized, where if necessary peak shaving gets priority. Demonstration of successful peak shaving in Couperus is to some extent obscured by 150 uncontrolled heat pumps. Controlling all 300 heat pumps will help substantiating the peak shaving results.

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