Suppressing Peak Load at Simultaneous Demand of Electric Heating in Residential Areas

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Abstract. High peak loads at distribution stations in domestic residences are expected where heating is provided merely by heat pumps with additional electric heating. Two scenarios are studied: the event of a black start and high electricity demand on a day with a very low outdoor temperature. The simulation is done with agents representing up to 100 dwellings based on PowerMatcher technology. The results demonstrate significant peak load reduction can be achieved at the expense of only a small decrease of comfort. This allows the usage of smaller load transformer units, reduces grid losses and benefits the lifetime of medium and low voltage transmission cables.

Keywords: Multi-agent, simulation, electric, heating, residential, distribution station, peak shaving.

1 Introduction

Currently in The Netherlands residential areas are built, aimed to reduce the energy consumption of households by using heat pumps for heating and cooling of all dwellings. Uncommonly for the Netherlands, in newly built areas there is no opportunity for a gas infrastructure. Several heat pumps are connected to an aquifer of which a few are present in the surrounding. Electric power is served by a local distribution station which serves about 150 houses equipped with heat pumps.

Although the houses are well insulated, it is expected that, on cold days, which may occur on the average only once or twice a year during a limited period of a few weeks, the power of the heat pump is insufficient to keep the temperature in the dwelling sufficiently high for user comfort. This is the reason why additional heating devices are present in the form of a simple electric resistance heating. As the power of the heat pump is typically 2.2 kW and the power of the auxiliary electric heating is 6 kW, the total power is much larger than the typical power of 1-1.5 kVA, available at the distribution level for a Dutch household. So the local distribution station, which serves about 150 similarly accomplished houses, and the transmission cables need to be designed for a much larger peak load, thereby raising costs and negatively influencing lifetime expectancy of the components.

Network companies facing these problems have wondered whether smart grid solutions can attribute to their design and maintenance problems by decreasing peak loads. During a field test with micro-CHP's, coordination of micro-CHPs using the PowerMatcher has shown this ability [1].

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They described two scenarios which would challenge a possible solution. One is the situation of a very cold day where heat pumps alone wouldn't be able to satisfy the habitants overall need for heat. The other is the situation where a blackout has occurred on a cold day, all the houses are cooled down and where at the blackstart all the houses demand a large amount of heat.

This is why software agents were designed and built for this case and used in a simulation to investigate the overall electric behavior and explore the possibilities of smart grid solutions based on the market algorithms the PowerMatcher employs [2].

According to the expected increase of the share of distributed energy resources in the electricity network, a proper integration operation of renewable devices into the network is necessary.

This study is performed as part of the Dutch project "SmartProofs", which aims at the development of a smart power system. This provides a proof-of-principle of successful integration of renewable energy sources in the electricity network with preservation of the guarantee of the delivery service. At the initialization of the project the focus was on the introduction of micro-CHP. During the course of the project the network companies involved in the project recognized that the introduction of heat pumps leads to the above mentioned scenarios with high peak loads. This has leaded to a shift of at least a part of the effort in the project to investigate heat pump related issues.

2 Multi-agent Systems and Electronic Markets

The multi-agent approach localizes and confines data, processing and controlling in a bottom-up fashion, without an omniscient top-level. In comfort control this has several benefits, such as 1) the generic description of installations 2) plug and play behaviour of appliances 3) adaptation to the circumstances instead of predefined behaviour and 4) no need for complex flow diagrams. For coordination of devices to match supply and demand in an electricity network, there has already been developed and tested a successful technology, 'the PowerMatcher'.

The PowerMatcher is a general purpose coordination mechanism for balancing supply and demand in electricity network [3]. This technique implements supply and demand matching (SDM) using a multi-agent systems and market-based control approach. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices in order to alter their operation in order to increase the over-all match between electricity production and consumption. Within a PowerMatcher cluster, the agents are organized into a logical tree. In this study the leaves of this tree are a number of agents representing a device. This agent tries to operate the process it is associated with in an economical optimal way.

The interactions of individual agents in multi-agent systems can be made more efficient by using electronic markets, which provide a framework for distributed decision making based on microeconomics. Microeconomics is a branch of economics that studies how economic agents make decisions to allocate limited resources, typically in markets where goods and services are being sold or bought. Whereas economists use microeconomic theory to model phenomena observed in the real world, computer scientists use the same theory to let distributed software systems behave in a desired way. Market mechanisms provide a way to incentivize parties (in this case software agents), that are not under control of a central authority, to behave in a certain way [4, 5]. A microeconomic theory commonly used in MAS is that of general equilibrium.

In general equilibrium markets all agents respond to the same price that is determined by searching for a price that balances all demand and supply in the system. An agent on such a market coordinates its actions with all other agents by buying or selling a commodity, here electricity. In order to do so, the agent communicates its latest bid (see below) to a so-called auctioneer and receives price updates from the auctioneer. The bids express to what extent an agent is willing to pay for or receive a certain amount of power; a request is converted to an adaptive price signal. As bids are constructed in a process of weighing the profits versus the costs, thus they represent the utility function of the agent. The bids are ordinary demand functions $d(p)$, stating the amount of electricity the agents wishes to consume (or produce) at a price p. After collecting all bids, the auctioneer searches for the equilibrium price p^*, i.e., the price that clears the market:

$$\sum_{a=1}^{N} d_a\left(p^*\right) = 0 \qquad (1)$$

where N is the number of participating agents and $d_a(p)$, the demand function of agent a. The price is broadcast to all agents. Individual agents can determine their allocated production or consumption from this price and their own bid.

Figure 1 is a schematically example of how the electricity market will try to balance demand and supply, taking into account the bids of all agents. he communication between device agents and an auctioneer is very limited. The only information that is exchanged between the agents and the auctioneer are the bids and the price. The auctioneer communicates the price back whenever there is a significant change. The PowerMatcher system thus optimally uses the possibilities of power producing and consuming devices to alter their operation in order to increase the over-all match between supply and demand real-time. It has been shown that a PowerMatcher cluster acts very well as a virtual power plant control [1].

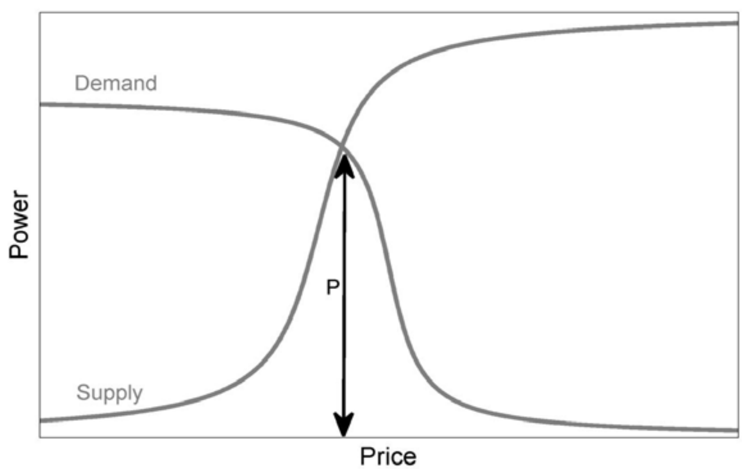

Fig. 1. Matching supply by representation of the bidding curves (P is the exchanged power)

3 Agent Design

For this specific case two software agents were developed i.e. a heat pump agent and a load agent.

3.1 Heat Pump Dwelling Agent

The heat pump dwelling agent represents a dwelling with a heat pump and auxiliary electric heating. A building model is incorporated in the agent, enabling the calculation of the indoor temperature. With the knowledge of the temperature and the set point temperature, certain strategies can be followed to calculate the amount of power demanded over the current price range. Knowing the price, the power can be determined that is allocated for both devices and the corresponding heat can be calculated which is released to the house, as well as the heat loss through windows, walls etc., depending on the outdoor temperature. The resulting room temperature is calculated after a certain time period, in a simulation typically 2 minutes.

The agent accounts for the preferred operation of a heat pump to be turned on for a longer time span T_{span}, e.g. 30 minutes, in order to obtain a good coefficient of operation (COP). This occurs once power is allocated above 2.2 kW. A power larger than this is allocated to the electric heating wire resistance. When this time span is passed and a power is allocated less than 2.2 kW, the power is allocated to the electric resistance heating. The set point value of the temperature depends on the presence and preferences of the habitant, which are resolved based on random parameters. A certain bandwidth around the temperature is employed, preventing the device from switching on and off too often.

In market based agent software like the PowerMatcher flexibility to a certain degree is needed [3]. As, besides peak load reduction, comfort for the inhabitant is the other major objective; it is chosen to incorporate in the bidding strategy a preference to supply more heat to those houses, which are the coldest. So the bid of the agent, which expresses the willingness to pay for heat, will depend on the indoor temperature. Thus implemented, it should be inferred from the results that the coldest houses are heated first.

Next to this, it proved to be beneficial for the heating of the houses, i.e. circumvention of overshoot of temperature, to implement a different bidding strategy when the difference between the indoor temperature and the setpoint value is below a certain value, $T_{Threshold}$, of about 2 °C. Under these circumstances heat from the heat pump is offered as usual, but the maximum amount of heat offered from the auxiliary electric resistance heating and hence the slope of the bidding curve is smaller and depends on the ratio of the actual temperature difference and $T_{Threshold}$.

3.2 Load Agent

The objective of the load agent is to prevent the supply of electricity from becoming so large, i.e. increasing above a certain maximum load, above which the likelihood of melting of the transformer is too large. In practice this means that the current or a certain representative voltage within the distribution station or even a certain temperature is surveyed and once this exceeds a certain cut-off value L_{cutoff}, which is smaller but close to the maximum $L_{maximum}$, a signal is send, preventing the demand agents from getting their full allocation. This translates for the PowerMatcher to a certain price increase of electricity, so that less electricity is supplied, but still within a region between L_{cutoff} and $L_{maximum}$.

In a simulation no current, voltage or temperature can be determined. However it is possible to derive the total power that is allocated by all heat pump dwelling agents. This is accomplished through the possibility of an agent in the PowermMatcher system to ask the auctioneer to send the aggregated bid and given the price, determine the load.

Opposed to practice, in simulations the size of the transformer unit can be varied to any extent. In this study $L_{maximum}$ is always chosen to be proportional to the number of houses and to be lower than the highest possible overall demand.

The heat pump dwelling agents are designed that no power can be consumed at the maximum price $P_{maximum}$. When the load becomes equal to $L_{maximum}$, the load agent is designed in such a way that the price will become $P_{maximum}$. The bid curve of the load agent is then almost zero at all prices. At loads below L_{cutoff} the price is allowed to become $P_{minimum}$, the bid curve of the load agent in this case has a high value at all prices. In the region between L_{cutoff} and $L_{maximum}$ the bid curve is near zero for low prices and has a high value above a certain load price, which is a parameter that is calculated by the load agent.

4 Results

The simulations reported here were performed with an amount of dwellings varying from 4 till 100 and an according maximum load $L_{maximum}$ for the transformer unit. The range of $L_{maximum}$ varied from 70% to 24% of the sum of the powers of the devices in all households.

Outdoor temperatures used in the simulation are actual recorded temperatures in 2000. Fig. 2 shows the result of a simulation with 4 dwellings at black start when outdoor temperatures are as low as 0 °C. As can be seen the total load does not exceed the $L_{maximum}$ and remains above L_{cutoff}.

The scenario of a cold winter morning was studied as well. Fig. 3 shows the result of a simulation with 20 dwellings. Indeed in this scenario the load does not exceed the maximum peak load.

Next the simulation was extended to comprise 100 dwellings represented by as much agents. Fig. 4 shows the total load on a substation on a cold winter’s morning with and without PowerMatcher control. In the uncontrolled situation a very high peak demand occurs after a black start. At about 6:30h another peak demand occurs due to households demanding heat for the comfort of their inhabitants as they wake up. Notice this peak is not as elevated as after the black start as people tend to wake up at different times, so the demand is a little outstretched in time. With the PowerMatcher control for 100 dwellings the load never exceeds the maximum permitted load which is 30% of the maximum load.

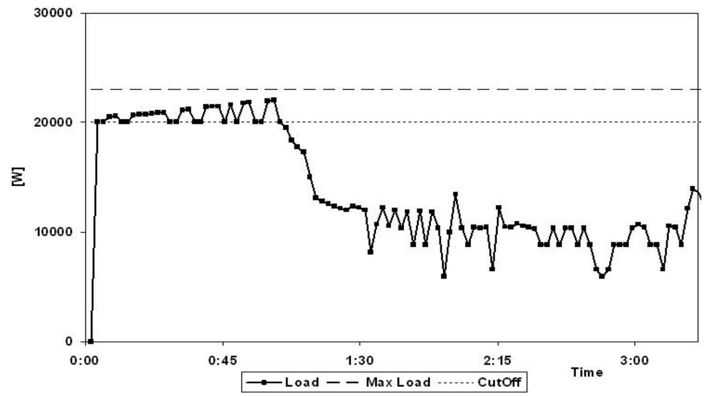

Fig. 2. Peak load reduction after a black start. The simulation comprises 4 dwellings and a distribution station operating at a maximum permitted load which is 70% of maximum load without control.

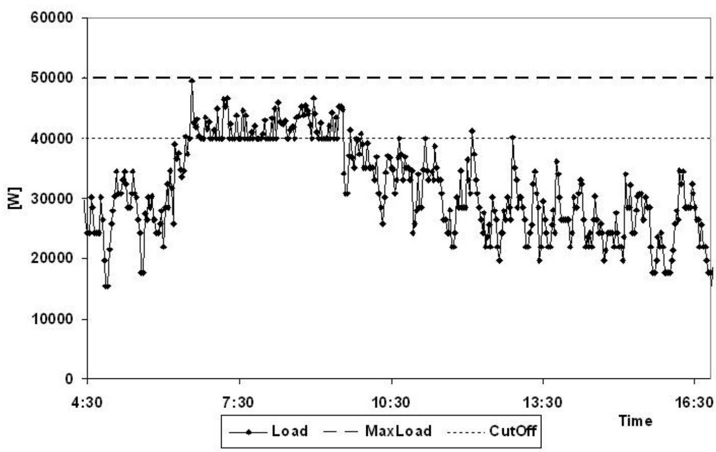

Fig. 3. Peak load reduction achieved at a substation on a cold morning for 20 dwellings. The distribution station operates at a maximum permitted load which is 30% of maximum load without control.

Since after a black start and at a cold morning in a PowerMatcher controlled situation less electricity is allocated for the heating devices of the household this means that less energy is available for heating the dwelling. This may result in decline of user comfort. To assess the extent of infringement with respect to user comfort the ascent of temperatures in a dwelling with and without PowerMatcher control were compared, which are shown in Fig. 5.

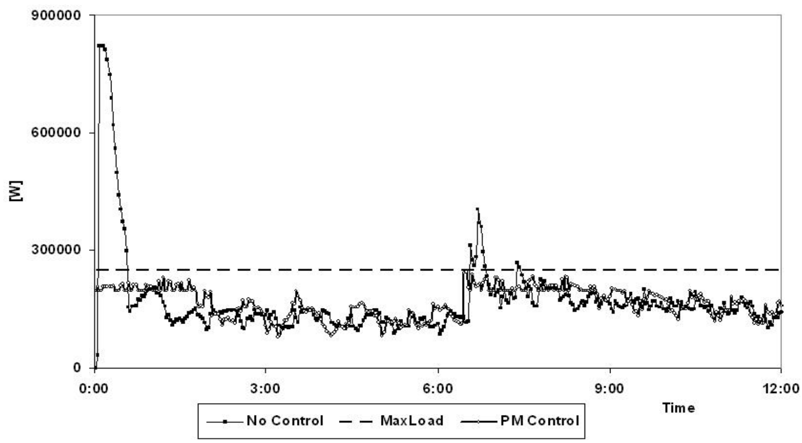

Fig. 4. Load at a substation for 100 dwellings after a black start and on a cold morning with and without PowerMatcher control. Maximum permitted load is 30% of maximum load without control.

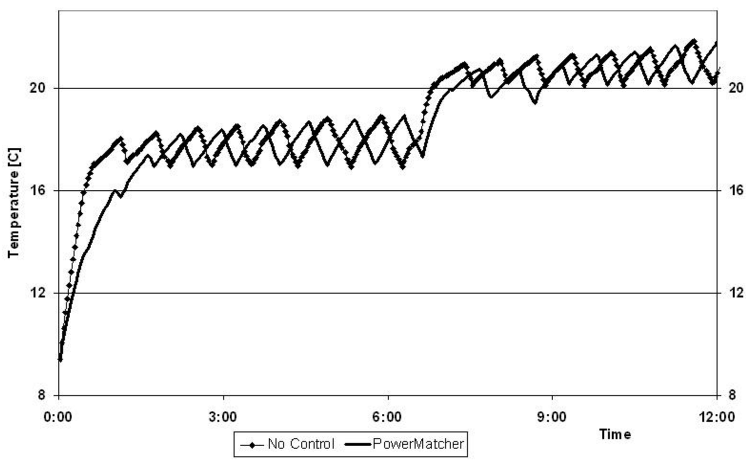

Fig. 5. Temperature in a dwelling with and without PowerMatcher control in a simulation of 100 dwellings. The initial temperature is 9 °C, the set point temperature at night is 17.5 °C and during the day 21 °C.

As can be seen from Fig. 5 the time it takes to reach the set point temperature in the controlled situation is delayed with respect to the uncontrolled situation, as is expected. However, the degree of delay may be quite acceptable.

The data of Fig. 4 can be transformed into a load duration curve, which is shown in Fig. 6. The large peak at the left of the diagram without control has disappeared in the controlled situation. Note that the surface below both curves are comparable, meaning that control did not affect the amount of energy (electricity) supplied to the dwellings.

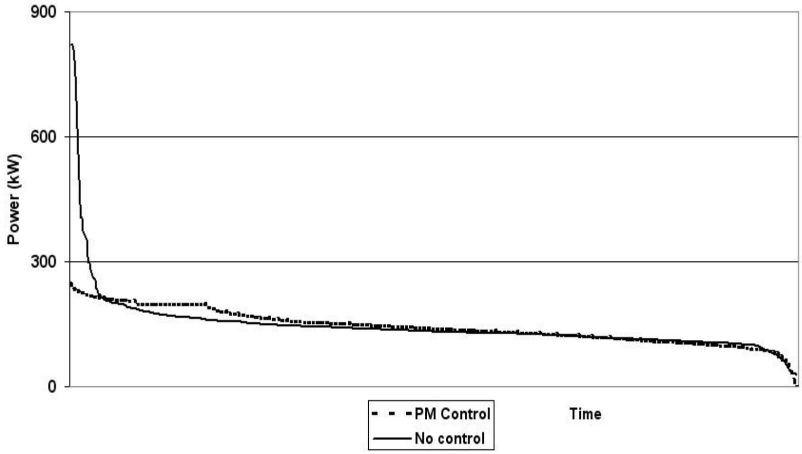

Fig. 6. Load duration curve for substation with 100 dwellings with and without PowerMatcher control. Maximum permitted load is 30% of maximum load without control.

5 Discussion

The simulation results indicate that, after a black start, reduction of peak load is possible. Fig. 2 shows that after a black start the load at a distribution station stays well below a certain maximum load and most of the time remains above a certain cut-off load. So the transformer can be protected against high loads exceeding the transformer limits, thus preventing it from melting. As also the longevity of the transmission cables will increase, PowerMatcher control offers potential benefit to the distribution system operator (DSO). This accounts for the low-voltage network as well as the medium voltage network which does not have to deliver high currents to the distribution station.

The power remains above a certain cut-off peak load. This means that after the black start the energy network hardly looses any capacity in delivering power and hence profit for the energy supplier as well. The equal ratio of surfaces below the load duration curves of fig. 6 further confirms this assumption.

Fig. 5 shows that all the houses can be heated immediately, meaning that, within the limits of the network, comfort returns to the habitants as soon as possible. With respect to the heat pump, it can also account for good operational circumstances, as the power is turned on for at least 30 minutes. It is not considered to be a problem if this time period needs to be a little longer in practice.

The rather steep rise of indoor temperature after change of set point value may be surprising considering the employment of heat pumps in combination with floor heating. Floor heating is associated with a slow process and it should take more time before reaching the set point value. The cause is due to a simplification in the building model heat pump agent. It is assumed that the heat generated by the heat pump is transferred directly to the dwelling rooms in stead of first to the floor. Although subject to improvement, with respect to peak reduction the essence of matter presented here is not affected by this simplification.

During a black out period some houses might become much colder than others. From a human physiology point of view, one might argue that those homes should be heated first as comfort sharply decreases with decreasing temperature [7]. The algorithm employed by the heat pump agents ensures that the coldest houses are heated first and the temperature difference between the houses is leveled out quite soon.

In this study the maximum number of dwellings is 100. This number can further be increased as there is no limit due to a maximum allowable number of agents running in a simulation or any other software or hardware limitation[1]. As the simulations were performed with 100 households this result favorably suggests that the algorithm is scaleable, as claimed by the real-time price based algorithm the PowerMatcher employs [3].

6 Conclusions

The simulation results suggest that using PowerMatcher control peak load reduction in a dwelling resort of up to 100 households is possible without hardly any infringement of user comfort. In the scenarios of a black start and in the morning of a cold winter day peak loads can be avoided.

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[1] On Microsoft Windows XP the maximum number of agents running on a single computer can be increased by setting MaxEndPoints in the registry to the desired value.

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