Real-time trade dispatch of a commercial VPP with residential customers in the PowerMatching City SmartGrid living lab

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ABSTRACT

An automated Virtual Power Plant using software agents bidding in an electronic market has been set-up in a living lab environment in Hoogkerk near Groningen using the PowerMatcher approach. The optimization goal of the cluster was to support trade dispatch of a commercial portfolio on the market. A trade dispatch objective software agent (TDOA) strategy has been developed allowing real-time response in the market taking into account prior optimization of demand response and power generation in view of the expected external day-ahead market electricity price as well as operational adjustments needed in view of the real-time position of the portfolio on external markets. The cluster was operated during a consecutive period of two months with a cluster of 25 homes equipped with either microCHPs or heat pumps for space heating both with hot water storage. Additionally, optimization of the charging process of 2 electric vehicles was included.

Analysis of the results shows, that the optimized TDOA power-profile can be followed by the agent for longer periods by utilizing the hot water buffering capacity and the battery capacity of the EV. Also, the buffering capacity is used automatically by the device agents to avoid price peaks in the case of heat pumps and to utilize them in the case of microCHP. The time scale at which the demand response can be delivered by the thermal processes in the homes and the EV-loads matches the required demand responses for trade portfolio operations in the Dutch system.

INTRODUCTION

In the Netherlands, the amount of energy necessary for heating homes and tap water production is about 1600 m^3 of natural gas, corresponding to approximately 16000 kWh_{th}. This figure can be compared to an average electricity consumption of households of 3500 kWh_{el}. Stirling engine based microCHPs and air-to-air heat pumps create interaction between the dynamics of thermal processes for heating homes and tap water delivery and the dynamics of the electricity system. With the inherent passive heat storage capacity of houses, the amount of flexible electricity supply/demand response via these heating systems is considerable. The potential can be further increased if the heating systems have hot water storage buffers not only for tap water but also for heating. For an electricity system, the value of aggregating many residential customers' devices to operate as a flexible and malleable Virtual Power Plant so far is only known from simulations.

In the Dutch city of Hoogkerk near Groningen in the Netherlands a SmartGrid living lab, PowerMatching City, consisting of 25 households, is in operation for almost three years now and was used to study VPP-operation in a number of SmartGrid use cases [1,2] showing the potential for compensating wind and PV imbalance. The hydraulics of the heating system allows the hot water storage to be used for space heating; the inhabitants of the homes do not notice management of the hot water buffer in terms of loss of comfort. In this way, the gas infrastructure can support the electricity infrastructure to avoid local peak loads or price peaks on the market. Another prospective source of flexible demand response is optimization of the charging of electric vehicles. In the living lab configuration, two electric vehicles were added with coordinated charging to help realizing the objectives of the cluster.

From the trade portfolio management perspective, a cluster with a large number of microCHPs and/or heat pumps provides a flexible power plant, which can be controlled without ramp-up and ramp-down times and without startup costs. Indeed, thanks to the granularity of power delivery, the ramp-up and ramp-down phenomena of other power plants in the portfolio can be compensated. Furthermore, the virtual power plant can be used to reduce imbalance on the market comparing the current realization of the portfolio with the day-ahead forecast.

OPTIMIZING DEMAND RESPONSE AND GENERATION

To generate an initial day-ahead profile for the VPP the electrical loads and generators in the cluster had to be forecasted for the next day. For thermal comfort systems in homes, the space heating demand depends on the expected outside temperature, the degree of cloud coverage and the wind velocity. In order to correlate the next day

expected temperature pattern to the heat demand pattern a best clustering algorithm using the Goodman-Kruskal [3] method was applied on a known dataset with temperature measurement profiles and corresponding heat demand profiles in representative Dutch households on a per-day basis. The best number of clusters to classify the correlation between outside temperature and heat demand according to the Goodman-Kruskal criterion was found to be 20. So 20 day-types were used to correlate the temperature pattern to the heat demand pattern. The next-day expected temperature profile was imported on a daily basis with 1 hour resolution from a meteo-service provider location. The profile was matched to the best fit with the average in the clustered set and yielded a forecast of the heat demand pattern. Subsequently, the electricity production and consumption profiles per device type were calculated using the conversion efficiencies of each technology also taking into account operational constraints of the devices. Below -4° C the heat pumps could not be operated due to frosting of the air outlets; in the homes, a gas fired boiler then came into operation. Similarly, at moment with high heat demand, the micro-CHP uses its peak burner. For the EVs, an initial peak charging profile was generated assuming charging just before the time of departure.

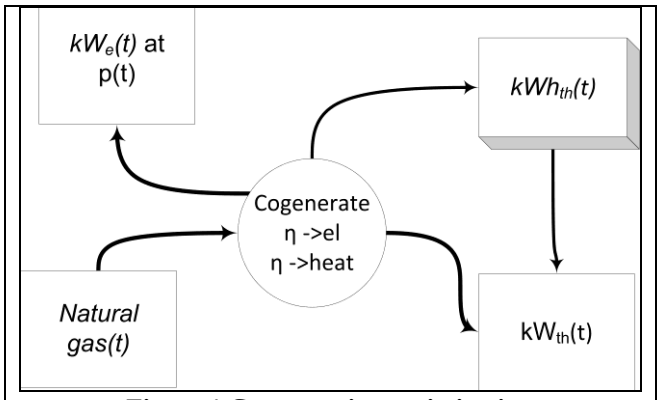

Figure 1 Cogeneration optimization

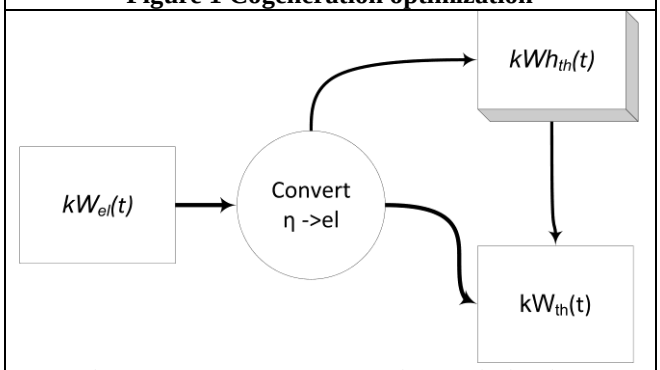

Figure 2 Heat pump conversion optimization

Finally, the resulting, device specific, power profile was optimized for an external price pattern (e.g. the next day market price) according to the B-Box algorithm [4] taking into account the central heating water storage capacity and the battery capacity respectively. Figures 1 and 2 illustrate the conversion and flows for the cogenerating microCHP and the heat pump. *Italics* denote variable time variable profiles that were the result of the optimization. There are two routes for heat to satisfy the heat demand; direct delivery or delivery via the buffer. The B-Box algorithm optimizes the proportion of energy usage via direct conversion and via conversion and storage in the buffer. The flow path variants were optimized in view of the day-ahead price. The 3D rectangle indicates the kWh storage capability as a function of time. The patterns were scaled and normalized to the actual measured production and consumption figures of the different types of comfort appliances for each home and the EV. Finally, the profiles were summed to yield the total profile of the VPP.

POWERMATCHER AGENT AND ICT DESIGN

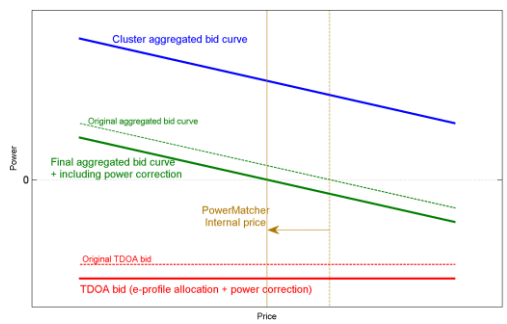

Figure 3 Bid-curve strategy for trade dispatch

The cluster was modelled as a PowerMatcher cluster [5]. The portfolio management functions were implemented in an objective agent called the Trade Dispatch Objective Agent (TDOA). Objective agents, in real-time, tune their bids in the market on the deviation of the forecasted profile from the realized profile [6]. So collection of data on the real-time aggregate electricity realization is necessary. The TDOA has a direct interaction with the PowerMatcher auctioneer, i.e. the highest market level in a PowerMatcher network [1,5], and with the commercial context of the cluster. So, in the VPP, the TDOA is the only agent, that has a perception of the non-PowerMatcher electricity market. Using this mechanism, the agent is able to translate an external market event (e.g. imbalance position or large power plant production optimization) into a PowerMatcher bid on the VPP PowerMatcher market. In this way, incentives can be given to the PowerMatcher coordinated virtual power plant (VPP). The TDOA is the PowerMatcher agent that interfaces to the energy trader.

The bidding strategy, in the form of a part of the bid curve, is depicted in Figure 3. A sample original aggregated bid curve in the cluster is indicated in blue depicting the amount of power at each price in the cluster. The dashed red line indicates the TDOA-bid based on following the day-ahead profile. The resulting equilibrium

power price is where the dashed green line passes the price axis. Adding an additional power correction leads to the green line indicating the resultant price in the cluster, at which the auctioneer allocates the devices in the cluster. In the current example picture, the incentive is given to reduce production. The price is lowered, leading to additional consumption from the heat pumps and EVs and less production from the microCHPs.

OPERATION OF THE CLUSTER

In contracts between parties on the energy market, time delineated, blocks with a fixed amount of power during a certain number of hours have to be delivered. With large power plants generation of power output shapes corresponding to blocks is not possible due to ramp-up and ramp-down delays. Assistance from flexible generators or the demand side is required. During portfolio operation on the market the real time realisation may differ from the forecast and depending on the current position of the imbalance market, it might be cost effective for a trader to impose additional deviations from the original cluster to the profile, that is followed.

In the TDOA use case a straightforward trading strategy was implemented: the TDOA always traded on the imbalance market, provided the cluster had the required flexibility available. Whenever the position of the national energy market was short, the TDOA offered capacity to the market by reducing energy demand or increasing energy production within the cluster. If the position was long, the TDOA operated in the opposite direction. Since the available capacity in the cluster is very limited compared to the total energy market, the capacity required by the imbalance marked was dimensioned proportional to the size of the cluster. The capacity was scaled by a factor 10^{-5}, yielding a required capacity of 1 kW (order of magnitude), against an average available capacity of approx. 10 kW. The load of the cluster was steered by the TDOA by bidding the required capacity against any price. The required load equaled the forecasted load, increased (or decreased) with the capacity needed for imbalance trading.

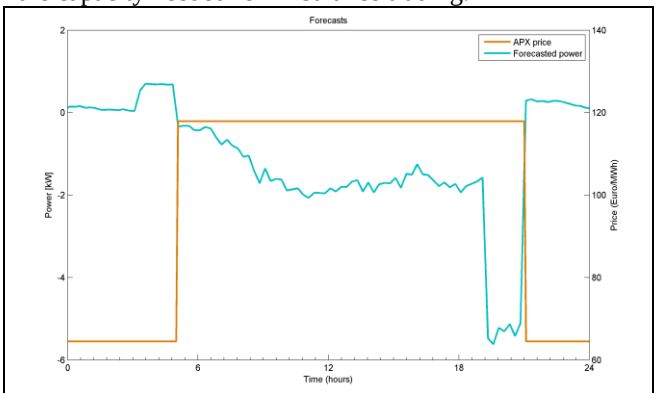

Figure 4 Power and price development during a day

In a use case depicted in Figure 4, the day ahead energy prices followed a conventional peak – off peak scheme (brown), both to examine the behavior of the cluster against this conventional scheme, and to minimize the impact of day ahead (time of use) pricing on the real time energy trading capabilities. The measurements were performed in the second half of the month November, with average outside temperatures of 5 °C. Figure 4 shows the realized power (in kW) for one full day in 15 minute time slots. A sharp power peak can be recognized shortly before the peak price period starts; also a strong power dip can be recognized before the low price period starts. This can be explained by the central heating buffers that are filled up completely by the heat pumps at low prices, and by the microCHPs at high prices respectively, before the prices alter.

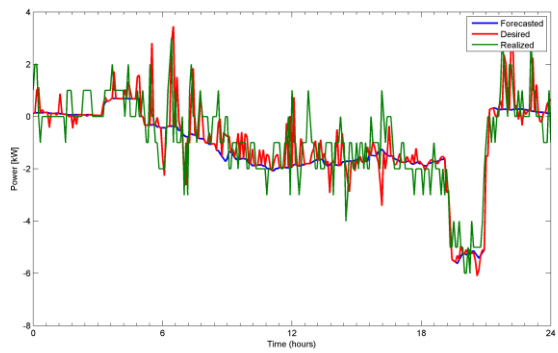

Figure 5 Forecasted, desired and realized power patterns

The forecasted, desired and realized power for realization with a more smooth APX-pattern are shown (in kW) in Figure 5 for one full day. The desired power equals the forecasted power, increased (or decreased) by the capacity offered to the imbalance market. The TDOA controls the cluster by requesting this capacity in real time. The realized power is the actual power provided / absorbed by the cluster, based on the allocation of the agents. Figure 5 shows that the cluster is well capable to provide/absorb the required capacity during the day. The trend is followed perfectly. The capacity offered to the imbalance market is actually achieved and can be capitalized; however the cluster itself seems to realize a continuous, though small, imbalance.

In general, the cluster has both the flexibility to deliver or absorb additional capacity. In certain situations (e.g. continuous steering to one extreme) the cluster may not have the flexibility to be steered in one direction. Figure 6 shows the available flexibility (in kW) during the day as derived from the summed PowerMatcher bid-curve equilibriums. This is depicted as the available capacity (in both directions: Upper_Ramp and Lower_Ramp), which approaches a relatively constant amount. The position of the cluster within these boundaries is depicted by the variable Mid_Ramp. It is expected that the position is primarily

influenced by real time steering, in this case trading on the imbalance market. The commercial aggregator steering volume, CA_Steering_Volume in the graph, shows the additional capacity that has been delivered or absorbed by the cluster.

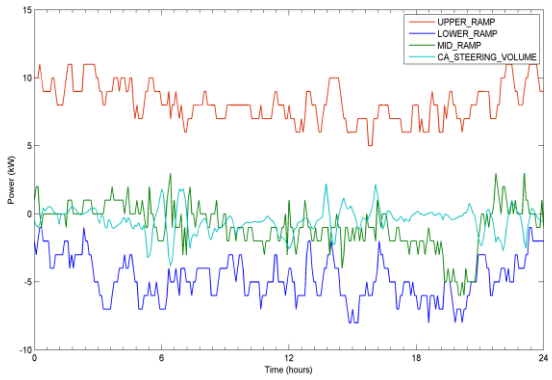

Figure 6 Ramp-up and ramp-down volumes

As expected, there seems to be a strong correlation between the steering volume (capacity traded on the imbalance market) and the position of the cluster (Mid_Ramp). This is especially true for the tendency, but less for the absolute figures. Although the available flexibility of the cluster is constantly out of balance (theoretically the Mid_Ramp would preferably proximate the x-axis), the cluster is mostly capable of delivering the required capacity. Maybe this imbalance relates to the observation in the previous paragraph that the realized capacity is not fully capable of following the desired capacity. At times when the Mid_ramp touches the lower_ramp, the internal 'coordination' price equals the minimum price and the cluster cannot reach an internal market equilibrium.

CONCLUSIONS & FUTURE WORK

The day ahead optimization by using forecasts on the basis of day-ahead energy prices in combination with intraday trading in a Virtual Power Plant approach worked well. Additionally, the Trade Dispatch Objective Agent approach proofed to be capable of trading on the imbalance market as well as compensating other real-time changes in the portfolio, thus creating value for the available flexibility.

The following conclusions can be drawn:

- The TDOA-agent is able to follow the profile for longer periods. This means, that the utilization of the buffering capacity of the heating devices and the EVs strongly increases the DR-potential.
- Pre-emptive reactions of devices can be shown through the distributed forecasting mechanism: heat pumps fill their heat storage buffers prior to expected price increases and micro-CHPs empty their heat buffers prior to expected price peaks in order to be able to produce electricity without an actual demand for heat. Electric vehicles automatically are charged at lowest price periods taking into account the planned departure time.
- The type of DR in the test appears to be extremely usable for compensating fast short-term market and portfolio fluctuations in the order of 5 minutes to 1.5 hours.

Currently, a successor project to the PowerMatching City project is running. In this project, Power Matching City II, the number of households in the VPP is increased. Additionally, to uncover further demand response, connected devices in PowerMatchingCity-II also include intelligent washing machines and dish washers.

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