Load control in low voltage level of the electricity grid using μCHP appliances

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***Abstract*—The introduction of μCHP (Combined Heat and Power) appliances and other means of distributed generation causes a shift in the way electricity is produced and consumed. Households themselves produce electricity and deliver the surplus to the grid. In this way, the distributed generation also has implications on the transformers and, thus, on the grid. In this work we study the influence of introducing μCHP appliances on the total load of a group of houses (behind the last transformer). If this load can be controlled, the transformer may be relieved from peak loads. Moreover, a well controlled fleet production can be offered as a Virtual Power Plant to the electricity grid.**

In this work we focus on different algorithms to control the fleet and produce a constant electricity output. We assume that produced electricity is consumed as locally as possible (preferably within the household). Produced heat can only be consumed locally. Additionally, heat can be stored in heat stores. Fleet control is achieved by using heat led control algorithms and by specifying as objective how much of the μCHP appliances have to run.

First results show that preferred patterns can be produced by using fleet control. However, as the problem is heat driven, still reasonably large deviations from the objective occur. Several combinations of heat store and fleet control algorithm parameters are considered to match the heat demand and supply.

This work is a first attempt in controlling a fleet and gives a starting point for further research in this area. A certain degree of control can already be established, but for better stability more intelligent algorithms are needed.

Keywords: microgeneration, modelling, algorithm design

I. INTRODUCTION

The Dutch electricity grid operator has to control the electricity distribution over the country. This grid origins from the situation, in which electricity is centrally generated in large power plants and in which distribution means distribution from these power plants towards customers. Therefore the grid consists of different voltage levels in order to reduce transportation losses over long distances. For long distances a high voltage is required, such that a lower current is sufficient to result in the demanded power. Transformers are used to switch from the one voltage level to the other. At the demand end of the grid, the voltage level is lower. Here, a set of houses is placed behind a last transformer.

The introduction of μCHP appliances and other means of distributed generation causes a shift in the way electricity is produced and consumed. Consumers themselves can produce electricity more efficiently [3] [2] and, moreover, they can deliver this electricity to the grid. Of course, this will have implications on the transformers and thus on the grid. The grid is obliged to accept electricity that is delivered to it below a certain amount per year. Since the electricity production of the μCHP is below the kiloWatt level, this amount is probably not reached and all produced electricity has to be accepted by the grid. If the use of μCHP is applied on large scale, problems will arise, since the combined households can produce a lot of electricity at the same time, which causes peak loads in the electricity grid. This means that the total production should be controlled at all time slices.

In this work we study the influence of introducing μCHP appliances on the total load of a group of houses (behind a last transformer). If this load can be controlled, the transformer might be relieved from peak loads. Moreover, a well controlled fleet production can be offered to the electricity grid as the product of a Virtual Power Plant. In the first control method we emphasize on heat led control, which gives priority to support a certain minimum heat demand in each household at each moment in time.

We focus on the last part of the electricity chain and the goal is to control the load on the last transformer (i.e. the production of the group of houses). In Section II-A a description of the model of the grid is given. The objective is explained in more detail in Section II-B. Based on this objective the control method is discussed in Section II-C and simulation scenarios are shown in Section II-D. Results are given in Section III.

II. APPROACH

The goal of this work is to develop μCHP controllers for in house use and fleet controllers that take care of a group of houses. These controllers together have to be able to give a stable grid, which means a controlled maximum load on the transformer and a stable electricity production. To test the developed control methods, a simulator for a group of houses is built [4]. First, we present the most important aspects of the simulator. Then the used control methods and different simulation scenarios are presented.

A. Model

Figure 1 models a group of houses behind a transformer, connected to the electricity grid. The contents of a house are shown in the same figure. A house has several (electrical and

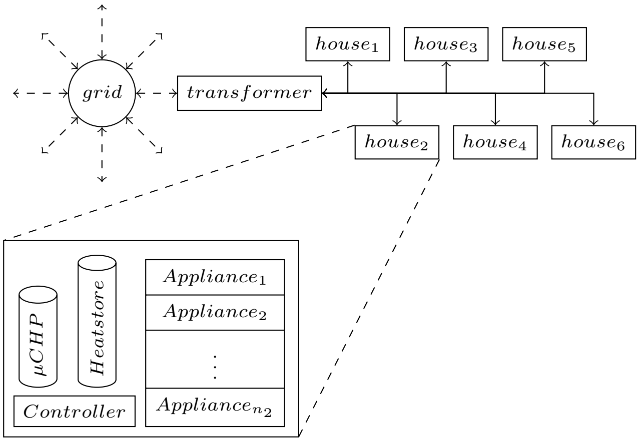

Fig. 1. Overview of the model

heat demanding) appliances, one μCHP, one heat store and a local controller. Global control is achieved in the grid (at the transformer). In the following paragraphs the model is explained in more detail.

1) Timing: The model uses a set of discrete time slices $T = \{0, \ldots, N_T\}$, which results in discrete control mechanisms that decide whether a μCHP appliance is switched on or off for the length of a complete time slice, opposite to other control mechanisms which might work in continuous time.

2) The grid: The model consists of a set of houses H, which are connected to the grid behind a single transformer. The houses are expected to exchange electricity locally in case of a surplus at one house and a shortage at another house. This implies that the load at the transformer is determined by the difference between the total production and the total demand (during a single time slice) within the grid. Note that the load can be both positive and negative; the sign switches with the direction of the electricity flow. The electricity production of house i on time $j \in T$ is denoted by PE_{ij} and the electricity demand by DE_{ij}. In this work we assume that the electricity demand data are given and deterministic. The load L_j on time slice j is defined as being the difference between generation and demand:

$$L_j = \sum_{i \in H} (PE_{ij} - DE_{ij})$$

This value is equal to the imported (in case of a negative load) or exported (in case of a positive load) electricity through the transformer at time j. The maximum load on the transformer is the maximum absolute L_j value during the planning period:

$$L_{\max} = \max_{j \in T} |L_j|$$

A fleet controller can be used to control the electricity production within the grid via influencing the number of μCHP appliances that are switched on in each time slice.

A factor, which can influence the control, is the electricity market. This market is modelled as part of the grid and, in the current implementation, uses average day ahead data to give an indication of the electricity prices during a day.

3) The house: A house $i \in H$ is modelled by a set of appliances $A_i = \{a_0^i, \ldots, a_{n_i}^i\}$, for which heat and electricity profiles are given. We denote by DE_{ijk} (DH_{ijk}) the given electricity (heat) demand of appliance a_k^i in time slice j. The electricity (heat) demand of a house DE_{ij} (DH_{ij}) is given by taking the sum of demands DE_{ijk} (DH_{ijk}) for all appliances in A_i.

Furthermore, a μCHP is installed in each house, together with a heat store. If the μCHP is running it produces a certain heat output and a certain electricity output. The heat output is stored in the heat store (resulting in an increased heat level in the heat store) or directly consumed by appliances with heat demand. Thus, next to an electricity production PE_{ij} we also get a heat production PH_{ij} for house i and time slice j. The electricity output is either used by the electricity demand of appliances or exported to the grid.

The μCHP has a controller that decides whether the μCHP is switched on or off for a complete time slice. The binary decision variable x_{ij} represents the on and off status of the μCHP of house i at time slice j. This decision is based on the energy level of the heat store and possibly also on the heat and electricity profiles and the prices on the electricity market. In the current implementation only the heat level h_i in the heat store of house i (with capacity hc_i) is taken into account. An upper level UL and a lower level LL on the energy level of the heat store are defined to determine the heat levels at which the μCHP must be switched off and on. If the μCHP is switched on it takes some time to work on full power. During this start up time the electricity production is lower than the production at full power, which is 1000 W in this work. The assumption is made that the electricity production increases linearly until it has reached its full power. The same holds for switching off the μCHP appliance (i.e. a linear decrease). Furthermore, due to technical constraints, there is a lower limit on the time the μCHP has to run before it can be switched off again. This minimum run time can have influence on the decision to switch a μCHP on or not. Besides UL and LL another heat level ML is introduced. This value gives the level below which an appliance may be switched on and, therefore, the difference between LL and ML gives the controller some freedom to schedule the electricity production of the fleet. An extra constraint is that when the μCHP is switched off, it has to stay off for a minimum period before it can be turned on again.

A given schedule (defined by x_{ij} values) now results in an electricity (heat) production profile of the fleet, given by the produced kWh per time period.

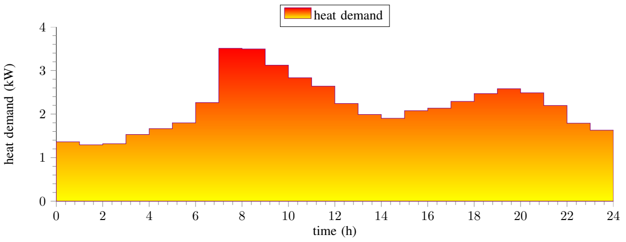

Fig. 2. Heat demand profile of an average winter day of an average house

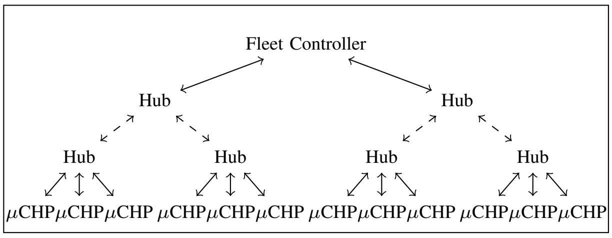

Fig. 3. The hierarchical structure of the control mechanism

4) Profiles: In the current implementation each house has the same appliances and thus the same electricity profile, since all appliances have the same non stochastic profile. The standard heat profile is derived from measurements taken at six houses for the durance of one week in winter [1]. This profile is shown in Figure 2. The heat demand adds up to a total of 52.625 kWh a day, which implies that the μCHP should run for approximately 6.6 hours at full generation mode to supply this demand (without taking startup times and shutting down times into account). The heat profile thus limits to a large extent the scheduling freedom of switching the μCHP on and off. If the minimum run time is half an hour, the startup period is 12 minutes and the switchoff period is 6 minutes, this implies that the μCHP is switched on at most 10 times per day, although it is still more preferable to have as little runs as possible due to wearing of the machine.

5) The controller: The μCHP appliances need to be controlled for several reasons, including the need for control mechanisms for a proper working of the installation and the connection to the in-house architecture. Our focus is on heat driven control, since it is important to guarantee to have a certain amount of heat available whenever there is demand for it in a household. This leads to local μCHP controllers that are suitable to supply the heat demand. However, eventually the most important aspect is to control the electricity grid. For this, we introduce a global controller that guides the local heat led controllers, while working on a global electricity led objective. The global Fleet Controller coordinates the control of the individual μCHP appliances, possibly via different Hubs. These Hubs are used to divide the fleet into groups with a limited number of houses. The lowest Hub is situated at a transformer. The resulting structure of the controllers is shown in Figure 3.

Each controller in the diagram must take the constraints (a certain production pattern) given from the level above into account. Each Hub can decide for itself how it reaches this objective or can split this objective into different parts, which are forwarded to Hubs in lower levels. For this research we consider only one global Fleet Controller and no Hubs.

B. Objective

Before describing the objective, two important aspects of the network are taken into consideration. First, the load of each transformer is of crucial interest. The transformer is adjusted to handle a certain maximum possible load. If this load can be reduced, this has a positive impact on the working of the transformer. Secondly, the electricity grid needs to be balanced. It is not possible to simply produce and consume electricity, whenever and wherever wanted. A proper 'harmony' between supply and demand is regulated by the electricity market and the grid is controlled by the network operator. Electricity is sold in predetermined batch sizes. If a Fleet Controller wants to act on this market, it has to be able to control the total production of a fleet of houses. Thus, in order to be able to make really use of all the electricity that is produced, the fleet as a whole needs to fullfill demand patterns that are given (e.g. by the Fleet Controller or by a certain Hub). More precisely, for each time slice j a preferable production amount OE_j (OH_j) for the whole fleet is given. Based on these given amounts OE_j or OH_j (which are deduced from heat and electricity predictions, both in households and in the market) we now consider as objective of the fleet controller to:

- minimize the mismatch between the fleet production and the specified amounts; i.e.

$$\min \sum_{j \in T} |OE_j - \sum_{i \in H} PE_{ij}|$$

or

$$\min \sum_{j \in T} |OH_j - \sum_{i \in H} PH_{ij}|$$

This objective is motivated by the structure of the electricity market. In this market a producer (in our case the fleet) has to specify in advance the amounts of electricity it wants to produce. These amounts have to be specified for small time periods (nowadays hours). In a first step we assume that the amount OE_j (and thus OH_j, since heat and electricity production is coupled directly) is constant over the time slices. This means that our choice for the preferable production is independent of the electricity demand of the houses in the fleet. The total electricity demand of the fleet is reduced by a constant; the control method is not aiming at peak reduction. However, for a first scenario this is a proper choice, since it allows to look at possibilities to schedule heat production of individual houses over a day. In later work the preferable production depends on both heat and electricity predictions in order to reduce electricity peaks better. For now, we concentrate on the heat demand.

C. Control method

The objective is to control the production of the fleet in such a way, that heat is generated according to a specified profile (OH_j values), which means in our case at a constant rate. By using μCHP appliances, there is a fixed ratio between the production of heat and the production of electricity. Since the individual controllers are heat driven, the heat profiles of the houses give a guideline for filling the heat stores. Therefore it is necessary that a control method that is developed for the production of a constant electricity rate, takes the heat store level into account. In general, in case of a higher demand in the heat profile, the μCHP runs longer, since filling the heat store goes slower. Also the time between two runs decreases, since the heat store empties faster.

These characteristics are depicted in Figure 4. If all households are supposed to have more or less the same heat profile (in our case the heat profiles are exactly the same), we observe

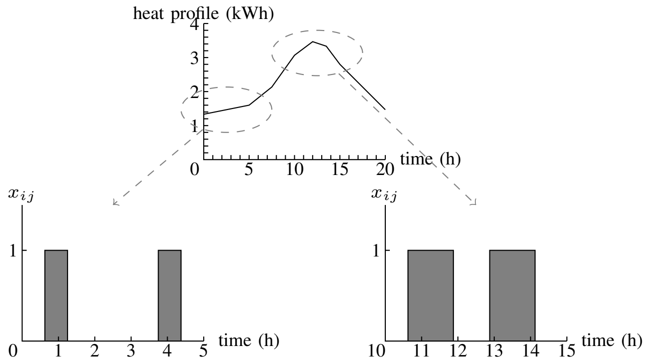

Fig. 4. The influence of the heat profile on the μCHP control

problems if we want the fleet to produce the same amount of electricity (and thus heat) in each time period. One way to solve this is to start a busy period (a period in which the heat demand is high) with the heat store as full as possible and to decrease the intermediate time between two runs as much as possible in calm periods. A good choice of LL, ML and UL already gives the opportunity to implement this solution in a simple control method (in which heat comfort is important). Besides the choices for these threshold values good OH_j values are necessary. These values have to be chosen such that the resulting heat production per day is approximately equal to the total heat demand per day, since we do not want to have large fluctuations in the starting levels of the heat stores for the next day.

The control method works as follows. The preferable production amounts OH_j can be transformed in preferred numbers ON_j of μCHP appliances which should run at full power in time slice j. The goal is to match this number as close as possible. Therefore the appliance with the lowest level in its corresponding heat store is switched on in case of a shortage of running machines, unless the heat store level is above ML. This level ML is set such that the minimum run time can be achieved in most of the cases without producing heat that cannot be stored for matching demands of appliances. As a consequence of this there is little heat loss. Furthermore, if the level of a μCHP runs below LL, this appliance is switched on, no matter how large the number of appliances currently running is.

In the current method we do not use any forecasting. The heat store level is recorded at the end of a time slice and in the next time slice the controller reacts to this information. However, if the fleet controller knows that in the following time slice a machine is stopping, automatically a new unit may start to produce, if the heat store level allows this.

If for a specific time slice we define R as the number of running μCHP appliances, h_i as the heat store level of house i and ON_j as the preferred number of running machines in time slice j, the working of the control method is presented in Figure 5.

Control method stable fleet production

```
Step 1  Initialization
        Set initial values $j = 0$, $R = 0$
Step 2  Use Individual House Controllers
        For all $i \in H$ DO:
        If ($h_i < LL$)
            Switch $\mu$CHP of $i$ on ($R := R + 1$)
        If ($h_i > UL$)
            Switch $\mu$CHP of $i$ off ($R := R - 1$)
Step 3  Use Fleet Controller
        Receive heat store levels and $\mu$CHP states
        from households
        While ($R < ON_j$)
        {
            If ($\min_{i \in H}\{h_i | \mu$CHP of $i$ off & minimum
            off period of $i$ passed$\} < ML$)
            {
                Switch on the $\mu$CHP appliance
                in household $i$
                $R := R + 1$
            }
            Else
                Go to Step 4
        }
Step 4  Update Individual Houses
        For all $i \in H$ DO:
        Update $h_i$
Step 5  Go To Next Time Slice
        $j := j + 1$
        If ($j < N_t$)
            Return to Step 2
        Else
            End
```

Fig. 5. The control method

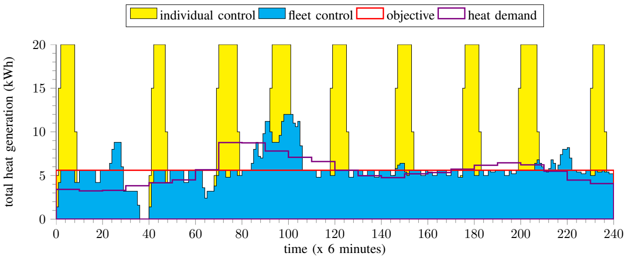

Fig. 6. Comparison of independent and fleet generation for a fleet of 25 houses (objective: 7 production units running at the same time)

With parameters $N_T = 240$, $|H| = 25$, $ON_j = 7$ for all time slices, $LL = 2$ kWh, $ML = 5.5$ kWh, $UL = 9$ kWh, $h_i = 5$ kWh and $hc_i = 10$ kWh set, Figure 6 shows as an example the results of the control method against an uncontrolled fleet. Individual control via independently operating households leads to an unbalanced heat (and thus electricity) production, while the control method follows the objective quite well for large parts of the time. However, some deviations, where the fleet cannot fullfill demand or leads to too much production, from this objective still occur. The deviations have two main reasons: shortages are due to heat demand that lags behind at the average preferred production for a considerable amount of time (all heat stores are ‘full’) and surpluses due to large positive differences between heat demand and preferred heat production (more heat stores need to be filled than preferred). Other small deviations follow from the fact that appliances do not work at full power during the startup and shutting down times, or result from the requirement that some appliances cannot be switched off before the minimum runtime has passed. In the figure also the total heat demand and the objective OH_j values are shown. The consequences of a positive and negative difference between these values for longer time periods are visible in the production by the fleet control method.

D. Simulation scenario

To show first results of our control method, we propose the following simulation scenario. In this scenario we compare the heat mismatch of using heat led control methods with different parameters, to the mismatch while using independent local controllers.

1) The scenario: We use a fleet of 25 houses. Each house has a Whispergen μCHP and a Gledhill heat store. The Whispergen has a generation level of 1 kW, a minimum runtime of half an hour, a startup time of 12 minutes, a stopping time of 6 minutes and a minimum off period of half an hour. The electricity:heat production ratio of the Whispergen is 1:8. The used heat store has a capacity of 10 kWh and a starting level of 5 kWh. The heat and electricity demanding appliances are the same in all houses and equal user profiles are defined for a single day.

For this fleet the parameters ML, LL and UL are varied. All simulations are run for the durance of a single day. For these scenarios the best match is found by varying the constant preferable μCHP appliances running ON_j from 1 to 25.

In order to find the best combination of heat store parameters and objective ON_j, the following penalty measure is defined besides the earlier mentioned heat mismatch:

$$\text{squared mismatch} = \sum_{j\in T}((\sum_{i\in H}(PH_{ij}) - OH_j)^2)$$

The ratio $\frac{\text{squared mismatch}}{\text{mismatch}}$ gives a measure for the occurence of mismatches. If this ratio is high, there is probably a small number of time slices in which there is a large difference between production and objective; if the ratio is low, the differences are more spread over the day.

III. RESULTS

In this section we discuss the results of the scenario and give our view at improvements that have to be made in future work.

A. Simulation scenario

Table I shows the results of the scenario, where an uncontrolled fleet is compared to fleet control. For the fleet control methods we defined the values $LL = 1$ kWh, $ML = 5.5$ kWh and $UL = 9$ kWh as basic parameters. These values are chosen such that every heat demand can still be fullfilled once the μCHP has to be started ($LL = 1$), that heat loss is avoided once the μCHP has to start stopping ($UL = 9$) and that the minimum runtime of half an hour can be achieved before the upper level is reached ($ML = 5.5$). The influence of changing these parameters with 1 kWh is shown in the table.

Control	LL	ML	UL	a)	b)	c)	d)
individual	1	5.5	9	7	1833	17529	9.6
fleet	1	5.5	9	7	194	550	2.8
fleet	2	5.5	9	8	253	1026	4.1
fleet	1	5.5	8	7	203	533	2.6
fleet	1	4.5	9	7	292	1105	3.8

a) best objective ON_j, b) mismatch

c) squared mismatch, d) $\frac{\text{squared mismatch}}{\text{mismatch}}$

TABLE I
MISMATCH FOR SIMULATION SCENARIO

The best objective value for ON_j is 7. In the basic case the average mismatch per time slice is 0.8 kWh, which is around 14% of the preferable production per time slice. The uncontrolled fleet has an average mismatch of 136% of the preferred value. The production mismatch can thus be reduced by almost 90% by using fleet control, compared to individual control by households. The squared mismatch is even more reduced, which shows that the fleet control methods result in a more stable production over the length of the day.

The parameter setting of LL and ML seems to be more important than a good value for UL. Lowering the level of UL even gives better results for the squared mismatch. An explanation for this is that the controller gets more freedom, since appliances are switched off earlier. On the contrary, a decrease of the level ML and an increase of LL decreases the decision freedom.

B. Future work

In future work the objective of minimizing the electrical current at the transformer can be addressed. New fleet controllers should be defined in order to handle electricity peaks. Before this can be looked at, a good prediction of the electricity load is necessary. This is an important aspect of further research. Once electricity usage and prices on the electricity market can be predicted, we can be able to define new non constant preferable production patterns OH_j that should be reached by the control method.

IV. ACKNOWLEDGEMENTS

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