Earliest deadline control of an energy source and a group of heatpumps with uncertain demand

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I. Introduction

Renewable energy sources are important for reducing carbon emission. There are many ways to integrate renewable energy into existing supply-demand chains. One way is to replace natural gas by biogas. In Meppel, a new urban area is to be equipped with a hybrid energy system with a Combined Heat and Power unit (CHP) at the heart of the system for the production of heat and electricity. The heat is transferred into a district heating system which is fed by multiple heat sources. The electricity is distributed to houses, each having a heat pump for space heating and domestic hot water.

Earlier we investigated centralized control options for this hybrid energy system, focusing on the optimal control of the heat pumps with the objective to balance electricity production by the CHP and demand by the heat pumps. In [2] we investigated a control method based on MILP (Mixed Integer Linear Program). Although this method properly balances electricity production and consumption and fulfill all energy demands as required, the optimization steers towards frequent shifting of the heat pumps, which is problematic for the efficiency and lifetime of the heat pumps. Therefore, in [1] we investigated possible solutions to improve steadiness or robustness of the heat pump and CHP control. We developed a control method based on earliest deadline theory and dynamic programming and we demonstrated that with this method it is possible to reach near-optimum control strategies within very short computational time with the desired robustness of the control of a large group of heat pumps and a central CHP.

In our previous papers [2], [4], [1], we assumed perfect prediction in our control strategies, i.e. all input data (e.g. occupancy related thermal gains and losses, ventilation and domestic hot water consumption) for the realization of the control are identical to the predicted values. Of course this is an unrealistic assumption since weather forecasts are not perfect and occupancy related schedules may vary substantially. This paper improves previous results by considering inaccuracies in predictions and it develops a control method based on earliest deadline theory which handles these inaccuracies.

II. Methods

In our model, every house is equipped with a single heat pump that provides energy for heating the house and hot water for the domestic hot water demand. The electricity powering all heat pumps is generated by a single Combined Heat and Power unit (CHP) with the purpose to provide electricity only for these heat pumps with as little support from the electricity grid as possible. The produced heat of the CHP is used to supply a district heating system which contains a thermal storage for daily balancing purposes.

Our model of the CHP only considers generated electricity because there are sufficiently large hot water tank in our case study. The CHP can operate in different modes and we denote by P the set of possible electric power values for these modes. For every time interval, our algorithm chooses one mode in which the CHP will operate. We pose the following objectives on the CHP control: the CHP should not switch the operation mode too often, heat pumps should only consume the electricity generated by the CHP and the overproduction of electricity should be minimal.

Every house is equipped with a heat pump which has three modes: generating energy for heating the house, generating energy for domestic hot water demand and being turned off. The domestic hot water output of the heat pump is connected to a buffer which stores the hot water for later usage. The house heating output is connected to a floor heating system which is a part of a thermodynamical model described in [3].

To study the quality of the control developed in this paper we perform a simulation with 104 houses; see [1] for more details. This paper improves previous results [1] by considering inaccuracies in predictions. In practice, some prediction tools (e.g. a neural network) can be applied to estimate data. In this paper, we consider a simplified approach to test the sensitivity of our method in inaccuracies: predicted data are obtained by the following randomization of the input data. Consider an input data series $d_1, \dots, d_n$, e.g. hot water demand or internal gains. The predicted value p_i for $i = 1, \dots, n$ is obtained from the Gaussian distribution with mean d_i and variance σ. We study three levels of inaccuracies of the prediction where the variance σ is 10% and 30% and 100% of the average of values $d_1, \dots, d_n$. Then, the randomized values $p_1, \dots, p_n$ are processed to avoid unrealistic values, e.g. ensure the non-negativity.

A. Control algorithm

Our approach is based on an online algorithm which has to decide operation modes of the CHP and all heat pumps for the coming time interval t_1. The control of the time interval t_1 is created from an energy plan for the near future consisting of a set of time intervals $T = \{t_1, \dots, t_n\}$.

Our algorithm is split between central CHP control and independent individual heat pump control. In every time interval, every heat pump controller provides to the CHP controller the lower $l_{h,t}$ and the upper $u_{h,t}$ bounds for the total electricity consumption up to the time interval t. The upper (lower) bound is the maximal (minimal) amount of electricity that the heat pump can consume during the first t time intervals. Essentially, the upper (lower) bound is determined by shifting electricity consumption to the earliest (the latest) possible time. There are various ways to calculate data required by the CHP controller and we applied the classical dynamic programming.

B. CHP control

The CHP control has two parts. The first part determines the amount of electricity produced by the CHP and the second one chooses which heat pump consumes electricity in the time interval t_1. In the second part, all heat pumps are sorted by their deadlines which is the first time interval with positive lower bound $l_{h,t}$. Electricity is provided to heat pumps in this ordering until the CHP output is reach.

In order to determine the amount of electricity produced by the CHP, the aggregated lower $l_t = \sum_{h \in H} l_{h,t}$ and upper $u_t = \sum_{h \in H} u_{h,t}$ bounds are calculated where H is the set of all heat pumps. Since we consider an online algorithm, we only have to determine the production p_1 for the coming time interval. Let p_0 be the power generated in the time interval preceding the time interval t_1. For every production level $r \in S$ we analyze what happens if the CHP production is changed to r for the coming time interval and kept for whole planning horizon. In this case, the total electricity production between the first and the t-th time intervals is rt and this value should be between l_t and u_t to avoid both underproduction and overproduction. However, the bounds l_t and u_t are calculated from the predicted data, so these bounds are considered as random variables. Using the cumulative distribution function of Gaussian distribution, we estimate the probability that rt is between l_t and u_t. Then, the expected number of time intervals e_r satisfying $l_t \leq rt \leq u_t$ is calculated for every $r \in S$. Let $r^\star$ the production level $r \in S$ maximizing e_r. The production level p_1 for the coming time interval is changed from p_0 to $r^\star$ only if $e_{r^\star}$ is significantly larger than e_{p_0} to avoid frequent flipping between two production levels.

III. Results and discussions

The simulation is performed for a week in spring to study the behaviour of our control during an average demand season and also for the coldest week in winter to verify how the control behaves during the peak demand period. Furthermore, we compare three levels of inaccuracies of predictions with a variance of 10%, 30% and 100% of the average of each data series.

Predictions and the improved control strategy introduced in this paper influence mainly the behaviour of the CHP. Figures 1 and 2 show results for the week in spring and in winter, respectively. It should be expected that better accuracy leads to smaller number of switches between production modes which is confirmed by the results. Furthermore, as the steering of the CHP in our paper is based on predicted values and not the exact values, the achieved results are not as good as the results in [1], which is unavoidable. However, the given results show that the performance of our methods is sufficient to be applied in practice. Furthermore, the presented algorithms also reasonably controls the system even under a very high inaccuracy of the prediction.

More detailed analysis of our results will be published in the full version of this extended abstract. Note that the main advantages of our approach remain: very fast computation (less than 1 ms per one house and one time interval) and very limited communication (only a single TCP/IP packet from every house in every time interval).

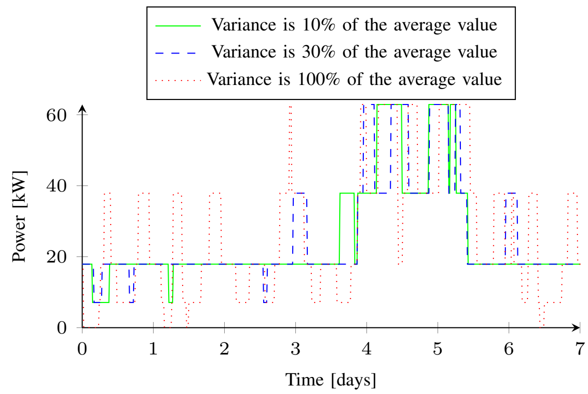

Fig. 1. Electricity produced by the CHP in spring

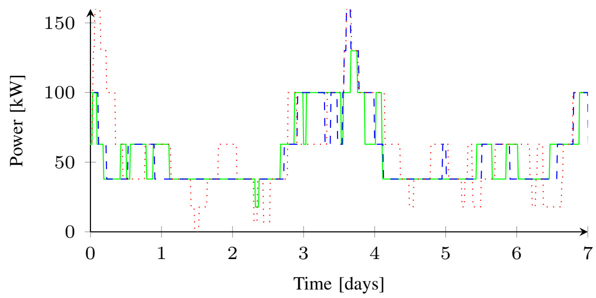

Fig. 2. Electricity produced by the CHP in winter

References

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