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Model predictive control for air conditioning systems in production sites

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Abstract

The change from fossil energy generation to an energy system mainly based on renewable energy sources requires innovative methods how energy is produced and consumed. The delivery profile of many renewable energy sources depends on the current weather conditions, what leads to a fluctuating energy generation. However, for a stable electricity grid a balance between consumption and generation has to be guaranteed all the time.

An energy and cost efficient method for balancing the system is demand-side-management. Flexible consumers combined with local storage systems are able to shift their demand to time periods with high generation. Examples for those flexible consumers are air handling units or compression chillers combined with cold storages. But to release the potentials of demand-side-management, new control strategies are necessary. They have to consider the future demand of the technical devices to make energy consumption to a predictable value. Like this building technologies are able to support the integration of renewable energy sources into the future energy system.

This paper presents a model predictive control strategy for air-conditioning systems in production sites, which uses prediction models of the building and the technical devices. Beside the main control strategy the development of the prediction models is focused in this paper. With the help of a genetic optimization algorithm an optimal operation schedule for the technical devices can be derived. During the operation an additional short-term load matching guarantees the accordance with the promised load profile.

Keywords – Smart Energy, Renewable Energy System, Demand Side Management

1. Introduction

An increase in the worldwide energy consumption about nearly 60 percent between 1990 and 2013 [1], rising energy prices and the limited availability of fossil energy sources necessitates a fundamental change in the energy supply system. Many industrialized countries already have started the conversion to an energy system, which is mainly based on renewable energy sources.

As an example, the percentage of renewable energy sources in the German electricity generation increased from 3.6 percent in 1990 to 30 percent in 2015 [2]. Generation units based on solar and wind power represent approximately 65 percent of the renewable electricity generation [2]. Changing weather conditions lead to a fluctuating generation profile and a direct control of the generation won't be possible in the future. Due to the fact that the amount of controllable flexible power plants (e.g. gas-fired power plants) will decrease at the same time and a balance between energy generation and consumption is essential for the stability of the power grid, new methods to balance generation and consumption have to be developed.

One possibility is an intelligent management of the demand side. Building devices, like air-handling-units (AHU) or compression chillers, are examples for flexible energy consumers. Floating set-points for the room temperature or additional storage devices (e.g. cold water storage) enable the energy management to affect the energy consumption in a desired way. The fact, that the operation of buildings in Germany nearly causes 40 % of the final energy demand [3], shows the high potentials for a demand-side-management (DSM).

Model predictive control strategies (MPC) enable an optimized operation of buildings, utilizing prediction models of the technical devices. In combination with weather forecasts and flexible electricity tariffs the electricity demand of the building is getting a predictable value and can be optimized with regard to different optimization targets (e.g. cost-efficient operation, user comfort, grid friendly operation etc.).

Since AHU and compression chillers show a high amount of flexibility and represent big consumers of electrical energy, the research work within the project "FOREnergy – Energy flexibility in production" focused on a MPC for air-conditioning systems in production sites. For additional testing, a small-scale hardware-in-the-loop demonstrator has been developed. Chapter 2 and chapter 3 give an overview about the models and the control strategy. An analysis and discussion of the results of an exemplary optimization follows in chapter 4. Finally chapter 5 summarizes the results and gives an outlook on future research work.

2. Modelling

The MPC uses simplified models of the building envelope and the technical devices in order to predict the electrical energy consumption of the air-conditioning system. To implement the models in the control system short computing times are needed so the models have to combine simplicity and accuracy at the same time. Fig. 1 gives an overview of the models, which have been used for this work. The air conditioning system has the functions ventilation, heating and cooling. In order to meet the cooling demand an air-cooled compression chiller with a screw compressor is used. In the optimization process of the MPC only ventilation and cooling are considered as flexible values, due to the fact that heating in Germany is mainly covered by fossil fuels (e.g. natural gas or heating oil).

The building model (based on VDI 6007 and 2078) is parameterized by using the geometry and physical properties of the building envelope. To derive the current cooling load of the air conditioning, an institution's internal model of an AHU [4] is integrated into the building model. Possible outputs of the combined model are the thermal cooling load, the power consumption of the fans and the expected room temperature.

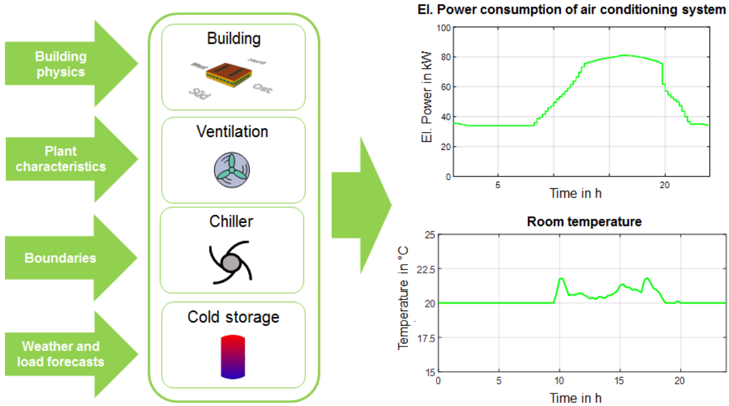

Fig. 1 Prediction models for model predictive control strategy

To derive the electrical power consumption from the thermal cooling load, a detailed model of an air-cooled compression chiller has been developed with the help of the Engineering Equation Solver (EES) [5]. The model can be parameterized by using technical data taken from the manufacturers of the components (compressor, condenser, evaporator, expansion valve). This allows the simulation of different chiller configurations. The model uses the thermodynamically substance database of EES to calculate the vapor refrigerant cycle. In this example the refrigerant R134a has been chosen.

For implementation of the model in the MPC, a simplified model is needed. Main influences on the power consumption of air-cooled chiller systems are the current cooling load and the ambient temperature. With a plant specific equation, which has been derived from simulation studies with the method of linear regression, the prediction of the Energy Efficiency Ratio (EER) is enabled. The EER describes the ratio between the supplied cooling power and the therefore needed electrical power. The equation is oriented to an equation, which is used to describe the operation data for compressors, taken from the DIN EN 12900 [6]. The specific EER, which has been used in the further work, is shown in Fig. 2.

To increase the flexibility of the whole system a sensible cold water storage is used. Sensible storage systems are really common and have low investment costs compared to other storage systems (e.g. phase-change-material storages). The storage model is defined by its maximum storage capacity in kilowatt-hours and has no heat losses to the environment. In future research work, this model will be replaced by a more detailed model, where also the effect of stratification and external losses will take into account.

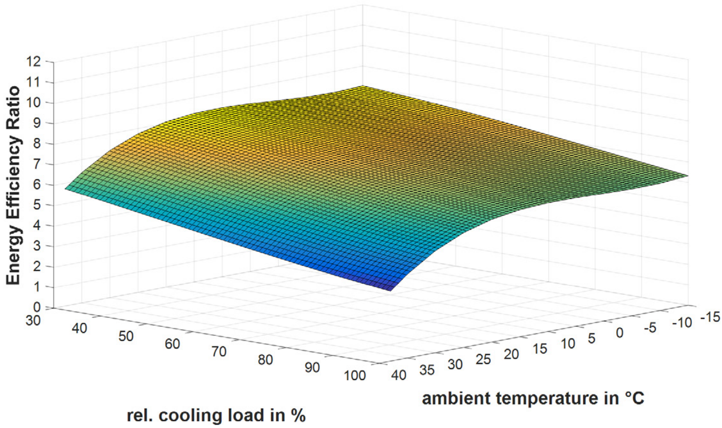

Fig. 2 EER of compression chiller ($R^2 = 0.99$)

The combination of the models with weather and internal load forecasts allows a prediction of the operation parameters as well as the reaction of the building climate. In Fig. 1 an exemplary electrical power consumption of the air conditioning system and the resulting room temperature in the production site are shown.

3. Model predictive control strategy

The adaption of the electrical power consumption to a specific optimization target requires flexibilities of the system. In addition to the cold storage, floating set points for the room temperature are used in this work. It is assumed that in an energy system with a high amount of fluctuating renewable energies the electricity prices are low at times of high electricity generation and vice versa. So the most cost efficient way of operation also supports the integration of renewable energy sources.

In the first step an operation schedule is derived within a long-term optimization. Schedules for the room temperature set point and for the usage of the cold storage are determined with the help of a genetic optimization algorithm in MATLAB. To avoid too high room temperature values allowed limits are defined. An optimization horizon of one day has been chosen for the long-term optimization, because the certainties of the weather forecasts for this prediction horizon are very good. Fig. 3 displays the optimization process graphically.

Also the objective function, which has been used for the optimization process is shown in (1). The three weighting factors allow a prioritization on energy costs (a), temperature deviations from the set point (b) or the usage of the cold storage (c). Additionally a penalty factor $F_{penalty}$ is included to avoid disregards of the defined temperature limits.

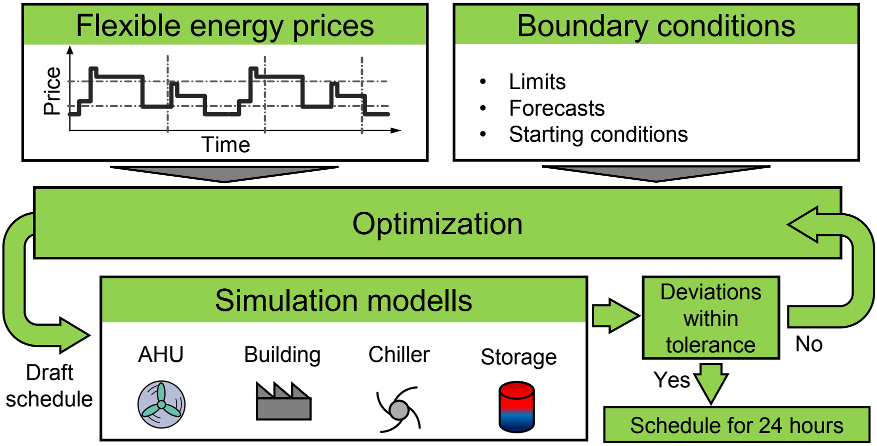

Fig. 3 Optimization procedure for daily optimization

$$Y = a \cdot K_{total} + b \cdot \Delta T_{sum} + c \cdot \frac{1}{sum(\dot{Q}_{stor,use})} + F_{penalty} \qquad (1)$$

with

a	-	*weighting factor for costs*
b	-	*weighting factor for temperature deviations*
c	-	*weighting factor for use of cold storage*
K_{total}	-	*sum of energy costs in €*
ΔT_{sum}	-	*sum of temperature deviations in Kh*
$\dot{Q}_{stor,use}$	-	*sum of storage use in W*
$F_{penalty}$	-	*penalty for disregard of temperature limit*

The derived operation schedules are transferred to the corresponding control systems. Nevertheless there has to be an additional monitoring during operation to avoid deviations from the promised power consumption. Incorrect forecasts for weather conditions or the internal load are possible uncertainties in the power prediction of the long-term optimization. Also inaccuracies of the prediction models could be a reason for those deviations. Therefore the short-term load matching monitors the actual power consumptions and in the case of a deviation tries to compensates them within a time horizon of fifteen minutes. An action list, which is classified in actions for power increase and power reduction has been defined. Additionally the actions are sorted according to their priorities, which means, that the actions with the lowest influence on the building climate has the highest priority. The action list, which has been used for the control of the air-conditioning system is shown in Table 1.

Table 1. Action list short-term load matching

power increase		
priority	action	boundaries
1	loading cold storage	▪ filling level of the storage ▪ max. loading power ▪ max. capacity of compression chiller
2	temporarily reduction of room temperature	▪ min. value for room temperature ▪ max. capacity of compression chiller
power reduction		
priority	action	boundaries
1	unloading cold storage	▪ filling level of cold storage ▪ max. unloading power
2	temporarily increase of room temperature	▪ max. value for room temperature

For testing purposes, the short-term load matching as well as the prediction models have been implemented in a programmable logic controller (PLC). The PLC is coupled with a thermal building simulation (TRNSYS) in a hardware-in-the-loop emulation test bench. This enables further tests of the control strategy under variable conditions. In Fig. 4 a schematic of the structure of the test bench is shown.

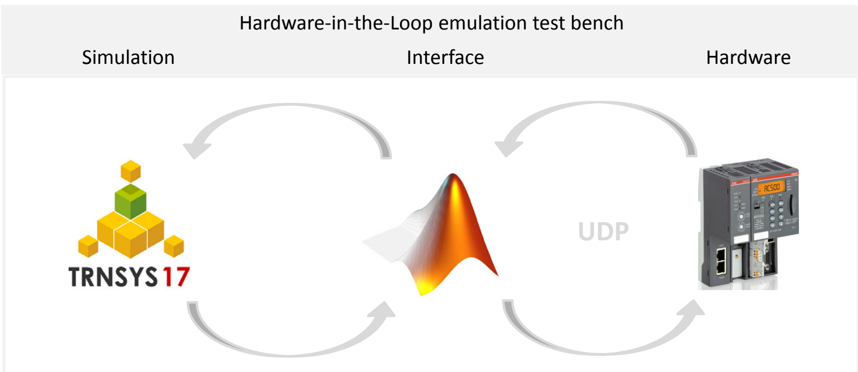

Fig. 4 Structure of the hardware-in-the-loop emulation test bench

The communication between TRNSYS and the PLC is managed by MATLAB with the help of the User Datagram Protocol (UDP). To provoke deviation between prediction and the current power demand the test bench is equipped with a touch panel, which allows a manipulation of the power demand.

4. Discussion and result analysis

This chapter concentrates on the results and the discussion of the optimization of an exemplary day. In the first part the long-term optimization will be analyzed. Afterwards the short-term load matching with a provoked deviation and the corresponding reaction of the control system is presented.

As mentioned above the long-term optimization is looking for the most cost-efficient operation schedule for the air conditioning system. Therefore a flexible electricity tariff is used, as shown in Fig. 5.

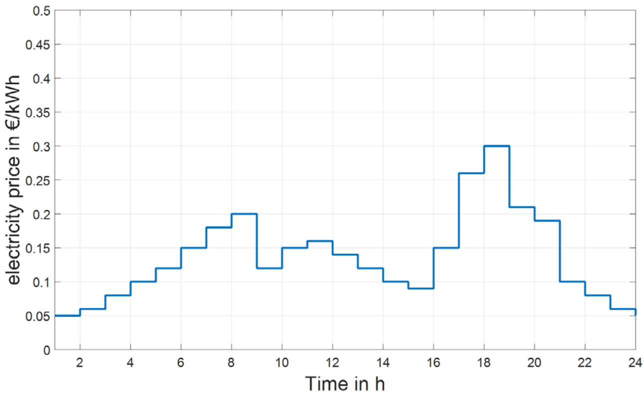

Fig. 5 Flexible electricity price curve

The price curve shows a typical behavior with a first peak in the morning and lower prices at midday, due to the high amount of solar power generation. In the afternoon the price is rising again to reach its maximum between 6 and 7 o'clock in the evening. Afterwards the price decreases till midnight to the low level of the morning.

To show the potentials of the optimization a day with a high cooling demand has been chosen. The maximum ambient temperature at this day is 33.9 °C. The solar radiation on the horizontal reaches values till 817 watt per square meter. The internal load is set to two stages. First there are 50 kilowatt (0:00 – 12:15) of internal heat load, in the afternoon there are only 20 kilowatt (12:15 – 0:00).

As a reference an operation schedule with a fixed temperature set point of 20°C has been chosen. In the reference also the cold storage is not used. The comparison of electrical power consumption of those two strategies is shown in Fig. 6. Especially in the afternoon the optimizer reduces the electricity consumption due to higher electricity prices. As a result the room temperature rises, what is also shown in Fig. 6. The allowed temperature limit has been set to 25°C, which is not crossed during the optimized operation schedule. Nevertheless it is getting obvious, that even in the normal operation the cooling power is not high enough to keep the room temperature at the defined set point of 20 °C. In this example the optimized operation leads to a cost reduction of nearly 6 percent compared to the reference operation.

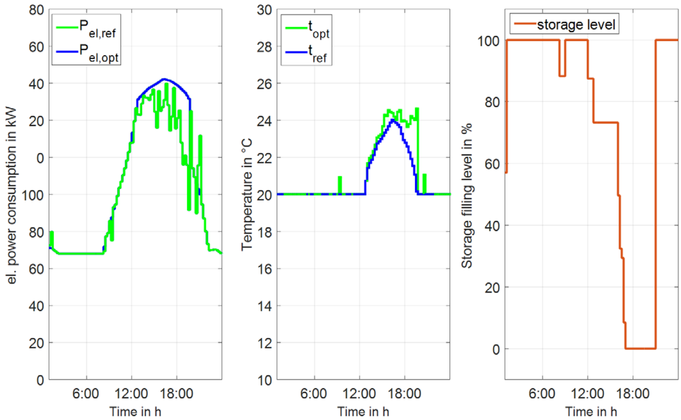

Fig. 6 Optimized electrical power consumption, resulting room temperature and use of long-term cold storage

The derived operation schedules for the components are transferred to the short-term load matching on the PLC of the emulation test bench.

Fig. 7 shows an example, where the power consumption has to be increased about 7 percent for one hour. The cold storage is able to compensate the deviation for an half an hour, if it is completely empty at the beginning.

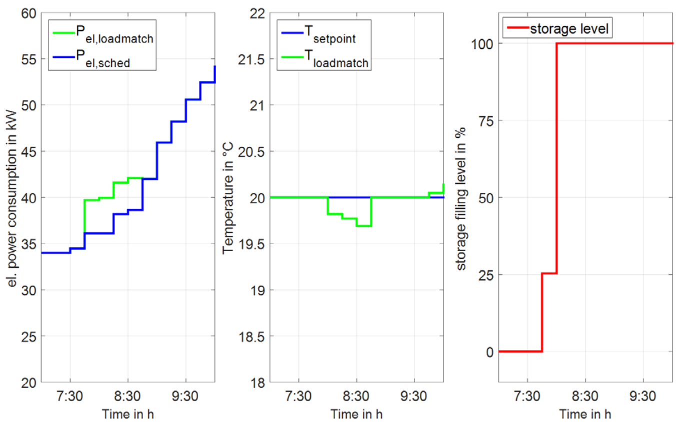

Fig. 7 Short-term load matching – Power increase

After the storage level reaches 100 percent, the set point temperature is reduced to fulfill the short-term requirements. Fig. 7 also shows the resulting room temperature and the filling level of the cold storage.

Fig. 8 shows an example for a power reduction. The storage level is set to 100 percent at the beginning. Also in this example the storage is able to balance the deviations for half an hour. Afterwards the consumption is reduced by accepting higher room temperatures as defined in the set point schedule.

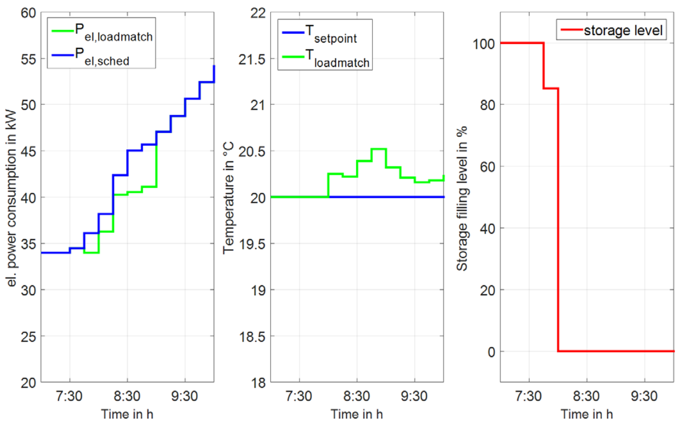

Fig. 8 Short-term load matching – Power reduction

5. Conclusion and future research

Facing the challenges of an energy system, which is mainly based on renewable energies, new concepts for energy generation, energy storage and energy consumption have to be developed.

Demand-side-management helps to integrate fluctuating renewable energy sources, like wind and solar power, into the power system. Building devices combined with model predictive control systems offer high potentials for flexible operation, especially if they are combined with additional storage devices. Air handling units and compression chiller are already widely spread and allow such a flexible operation. In the future the potential will even increase, because electrical driven heat pumps are getting more and more common for heating purposes. The paper has shown an exemplary model predictive control for an air-conditioning system combined with flexible energy tariffs. The optimized operation leads to reduced energy costs compared to the reference operation schedule. To avoid deviations between the promised and the resulting power consumption and additional short-term load matching is necessary.

But especially for small energy consumers there are too much barriers to use a model predictive control systems. So a high effort is necessary for parameterization of the system, especially for the prediction models. Universal models for the building and the technical devices are needed to simplify the commissioning process.

Also missing flexible energy tariffs for small energy consumer constrain the distribution of demand-side-management in Germany. At the moment there is no economic incentive for flexible operation and for investment in innovative flexible devices.

Future research work should address the simplification of the models, for example with the help of neuronal networks. Such models could be parameterized by using historical data or by defining a learning phase after the first commissioning process. But also the economical factor has to be addressed more and the development of new pricing concepts for electricity is necessary.

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