Modelling and design of a linear predictive controller for a solar powered HVAC system

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***Abstract*—The world's increasing population growth has led to a rapidly rising building sector. A major source of global energy consumption are buildings and heating, ventilation and air-conditioning (HVAC) systems. Therefore, the energy-efficient operation of buildings and HVAC systems as well as the optimal use of renewable energy sources have become the crucial factor with respect to the goals of reducing energy consumption and hence contribute to the desired climate change mitigation. More intelligent automation and control for buildings and their energy systems represent a simple and cost-effective way how to achieve the desired goal of lower energy consumption and to promote the use of alternative energy sources. In contrast to the conventional control approaches, employing model based predictive control techniques provides for the possibility to exploit the potentials of the controlled HVAC systems in a larger scale and therefore contribute to the energy efficient building operation. This paper presents the design of a model based predictive controller for a solar powered HVAC system. The advantages of the predictive control concept are emphasized on the basis of a comparison of the MPC control approach supplied with correct and incorrect weather forecast information.**

I. Introduction

In 2007 the European Union called out climate and energy goals to be reached by 2020. These goals included the reduction of greenhouse gas emissions by at least 20% compared to the 1990's levels, and to increase the use of renewable energy sources to account for at least 20% of the overall energy consumption as well as the reduction of primary energy consumption by 20%, see e.g.: [1].

According to [2] the building sector accounts for around 40% of the global energy consumption, whereas HVAC systems represent 50% of the end-energy use in buildings [3]. There have been proposed several technologies to tackle the issue of energy efficiency for the sector of new but also existing buildings such as better insulations (e.g.: [4]), more energy efficient appliances for heating as well as cooling (e.g.: [5]) and active solar design (e.g.: [6]). Furthermore, there is a trend towards an increase of the use of renewable energy sources (see e.g.: [7]).

Promising results on alternative approaches to increase energy efficiency have been reported for instance in [8], where improved control strategies of building systems have shown a decrease of the overall energy consumption. As outlined in e.g.: [9] improving HVAC system control represent the most cost-effective way to achieve energy efficient building operation.

The employment of model based predictive control (MPC) concepts is very common in process industry as well as in several research areas showing outstanding performance (see e.g.: [10], [11] and [12]). In building control there is still a lack of MPC applications. However, its advantages with regards to optimal control and its predictive character to consider the real system's future dynamic behaviour have attracted great attention within the building research community.

The work [13] considers MPC for temperature control in buildings. Hereby, the future building temperature dynamics is evaluated on the basis of a physical model and the MPC approach performance is compared to the traditional PI control concept. [14] reports on the use of implicit MPC to reduce energy consumption in a building. Thereby, incorporating weather forecast information, energy savings up to 10% could be achieved. The authors in [15] employ predictive control to maintain thermal indoor comfort using HVAC systems. Energy consumption is considered hereby as well.

This work addresses predictive control of a solar powered HVAC system. The predictive controller considers weather data to obtain the optimal control input trajectories. The control target is defined such that the solar radiation is used in an optimal way. The energy consumption of the actuators is considered here within the frame of a cost function. In the first step, the system consisting of a solar collector field, heat exchanger and a stratified storage tank as well as actuating pumps is modelled using first principle laws to obtain its dynamic behaviour. The flow rate depended time delay due to the large solar collector field is considered here as well. In the second approach a model based predictive controller is designed on the basis of the system model. In the following the predictive concept is analysed in simulation studies incorporating correct and incorrect weather forecast information.

II. Mathematical modelling of the HVAC system

In this section the mathematical model of the HVAC system installed in the EnergyBase building is provided (office building with passive house standard, see [16]), being suitable for the design of the model predictive controller. The preferred formulation of HVAC model equations is state space. The HVAC system configuration is shown in Fig. 1. The multiple-input-multiple-output (MIMO) model based predictive con-

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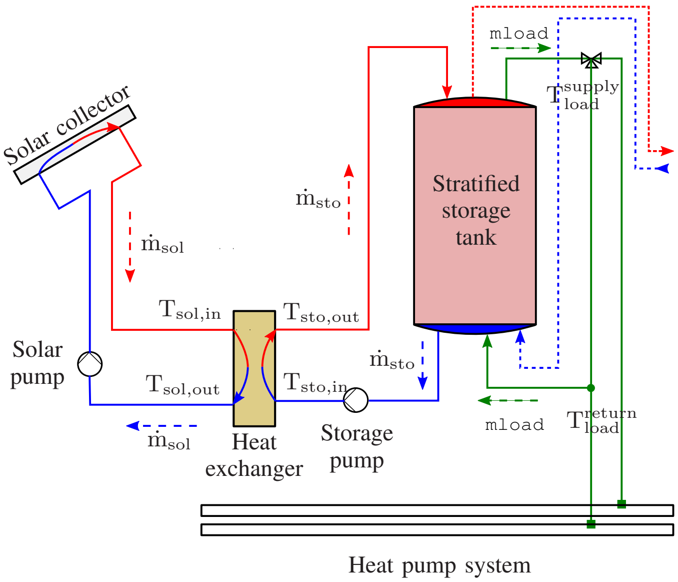

Fig. 1: Schematic description of the solar powered HVAC system of the EnergyBase office building.

troller is using the solar pump and the storage pump as actuators. The goal is to control the temperature differences at the inlet and the outlet of the heat exchanger (i.e.: $\Delta T_{sol} = T_{sol,in} - T_{sol,out}$ and $\Delta T_{sto} = T_{sto,out} - T_{sto,in}$) for a defined operating point. The pumps are turned on and off on the basis of weather data, where the solar radiation serves as the decision value for turning on or off respectively. The control concept structure is provided in Fig. 2. T_{amb} and G_t denote the ambient temperature and the global solar radiation (i.e.: the sum of direct and diffusive radiation) respectively. Both are considered as disturbances by the controller, therefore being subject to rejection. $\dot{m}_{load}$ is considered as the disturbance acting on the storage tank as an impact of the tapped water due to the heat pump system as well as the thermally activated building system for heating and cooling. $\dot{m}_{sto}$ and $\dot{m}_{sol}$ act as the manipulating variables with regards to the feedback HVAC control.
In the following a mathematical representation of the components of the controlled HVAC system is provided.

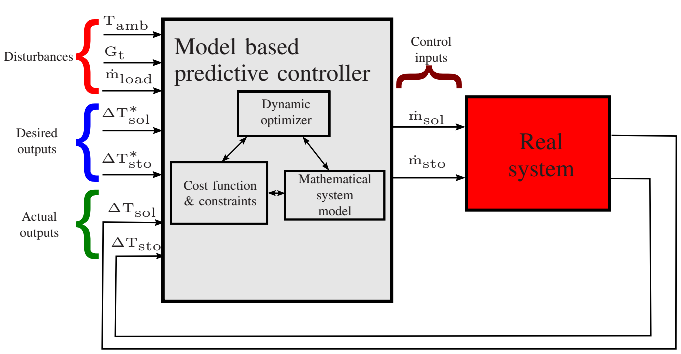

Fig. 2: Control concept structure for the solar powered HVAC system.

A. Heat exchanger dynamic model

In this work the heat exchanger is modelled using a second order system of differential equations by means of process lumping (i.e.: one node each for the primary and the secondary circuit) as shown in e.g.: [12] and [17]. The state equations describing the heat exchanger states for the time periods where the solar and storage pumps are activated are provided in Eq. (1) and (2).

$$\text{if } \dot{m}_{sol} > 0 \text{ and } \dot{m}_{sto} > 0 \tag{1}$$

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}T_{sol,out} &= \frac{1}{M_{sol}c_{sol}}(\dot{m}_{sol}c_{sol}\left(T_{sol,in} - T_{sol,out}\right) \\ &\quad - A_{hex}U_{hex}\Delta T_{mean}) \\ \frac{\mathrm{d}}{\mathrm{d}t}T_{sto,out} &= \frac{1}{M_{sto}c_{sto}}(\dot{m}_{sto}c_{sto}\left(T_{sto,in} - T_{sto,out}\right) \\ &\quad + A_{hex}U_{hex}\Delta T_{mean})\end{aligned}$$

else

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}T_{sol,out} &= \frac{\kappa_{sol}}{M_{sol}c_{sol}}\left(T_{amb} - T_{sol,out}\right) \\ \frac{\mathrm{d}}{\mathrm{d}t}T_{sto,out} &= \frac{\kappa_{sto}}{M_{sto}c_{sto}}\left(T_{amb} - T_{sto,out}\right)\end{aligned} \tag{2}$$

with

$$\begin{aligned}\Delta T_{mean} &= \frac{1}{2}\left(T_{sol,in} + T_{sol,out}\right) \\ &\quad - \frac{1}{2}\left(T_{sto,in} + T_{sol,out}\right)\end{aligned}$$

For time periods where the solar and storage pumps are not running, Eq. (2) considers purely heat losses to the ambience.

B. Solar collector dynamic model

In the EnergyBase HVAC system a flat plate solar collector field is installed. Solar collectors are employed to convert solar radiation to internal energy of the liquid being transported (see e.g.: [18] for more information).
In this work we are using a one node approach according to Fig. 3 considering the time delay τ_d due to the large length of pipes. $\tilde{T}_{col,in}$ presents the time delayed inlet collector temperature. Σ_{col} summarizes the collector outlet temperature dynamics and is given in Eq. (3) and (4) where both the solar pump on and off periods are considered.

$$\text{if } \dot{m}_{sol} > 0 \tag{3}$$

$$\begin{aligned}\dot{T}_{col,out} &= \frac{1}{M_{col}c_{sol}}(A_c c_0 G_t - A_c c_1\left(T_{col,out} - T_{amb}\right) \\ &\quad - A_c c_2\left(T_{col,out} - T_{amb}\right)^2) \\ &\quad + \frac{\dot{m}_{sol}c_{sol}}{M_{col}c_{sol}}\left(\tilde{T}_{col,in} - T_{col,out}\right)\end{aligned}$$

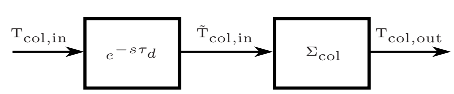

Fig. 3: Total dynamics between the inlet $T_{col,in}$ and outlet $T_{col,out}$ temperatures of the solar collector.

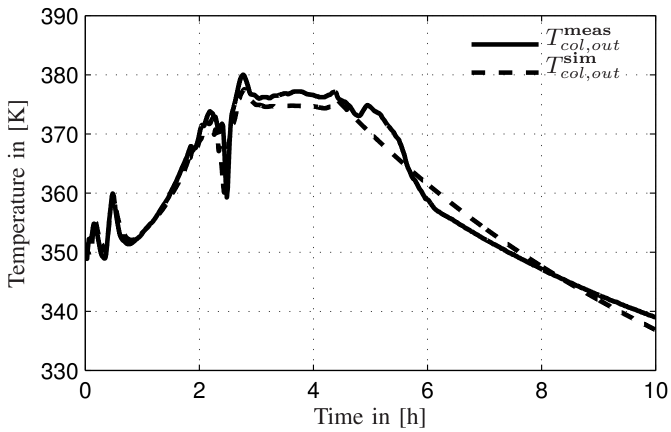

Fig. 4: Validation of the solar collector model using measurements.

else

$$\dot{T}_{col,out} = \frac{\kappa_{col}}{M_{col}c_{sol}}\left(T_{amb} - T_{col,out}\right) \quad (4)$$

with

$$\tilde{T}_{col,in}(t) = T_{col,in}(t-\tau_d)$$
$$\tau_d = \frac{\rho A_c L_{col}}{\dot{m}_{sol}} \quad (5)$$

The time delay τ_d from Eq. (5) was identified through measurements and can be approximated by $\tau_d \approx 300/\dot{m}_{sol}$. As can be seen in Fig. 3 the time delay can only be approximated in frequency domain using the transcendental function according to $e^{-s\tau_d}$. However, as we pursue a systematic approach towards the design of the model based predictive controller it is more convenient to obtain a compact form of the HVAC system dynamics. Therefore, the dead time transfer function $e^{-s\tau_d}$ is approximated using a Padé approximation of order 4 (see e.g.: [19]) as provided by Eq. (6).

$$e^{-s\tau_d} \approx \left(\frac{1 - s\frac{\tau_d}{8}}{1 + s\frac{\tau_d}{8}}\right)^4 \quad (6)$$

Fig. 4 illustrates the validated model including the time delay τ_d and its 4^{th} order Padé approximation.

C. Stratified storage tank dynamic model

Due to its high thermal capacity the stratified storage tank can be considered in this HVAC system as the component showing the slowest dynamics. With respect to the subsequent controller design that means that it introduces a high degree of stiffness. A schematic description of the tank is given in Fig. 5 for which the layers are supposed to illustrate the stratification effect. The model state space representation is given in Eq. (7) where 20 nodes are considered (i.e.: $N = 20$).

if k==1 (7)

$$\dot{T}_{st,1} = \frac{\dot{m}_{sto}c_{st}}{M_{st,1}c_{st}}\left(T_{sto,out} - T_{st,1}\right)$$

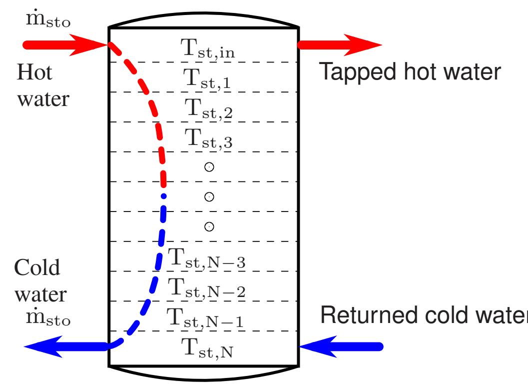

Fig. 5: Sketch of the stratified storage tank used for controller design.

$$- \frac{\dot{m}_{load}c_{st}}{M_{st,1}c_{st}}\left(T_{sto,out} - T_{load}^{\text{supply}} + T_{st,1} - T_{st,2}\right)$$
$$+ \frac{A_{st,1}\lambda}{M_{st,1}c_{st}z_{st,1}}\left(T_{st,1} - T_{st,2}\right)$$
$$- \frac{\kappa_{st,1}}{M_{st,1}c_{st}}\left(T_{st,1} - T_{amb}\right)$$

else if k==20

$$\dot{T}_{sto,in} = \frac{\dot{m}_{sto}c_{st}}{M_{st,20}c_{st}}\left(T_{st,19} - T_{sto,in}\right)$$
$$+ \frac{\dot{m}_{load}c_{st}}{M_{st,1}c_{st}}\left(T_{load}^{\text{return}} - T_{sto,in}\right)$$
$$+ \frac{A_{st,20}\lambda}{M_{st,20}c_{st}z_{st,20}}\left(T_{st,19} - T_{sto,in}\right)$$
$$- \frac{\kappa_{st,20}}{M_{st,20}c_{st}}\left(T_{sto,in} - T_{amb}\right)$$

else

$$\dot{T}_{st,k} = \frac{\dot{m}_{sto}c_{st}}{M_{st,k}c_{st}}\left(T_{st,k-1} - T_{st,k}\right)$$
$$+ \frac{\dot{m}_{load}c_{st}}{M_{st,k}c_{st}}\left(T_{st,k+1} - T_{st,k}\right)$$
$$+ \frac{A_{st,k}\lambda}{M_{st,k}c_{st}z_{st,k}}\left(T_{st,k-1} - 2T_{st,k} + T_{st,k+1}\right)$$
$$- \frac{\kappa_{st,k}}{M_{st,k}c_{st}}\left(T_{st,k} - T_{amb}\right)$$

with $k \in [1, 20]$

The storage tank model from Eq. (7) considers terms to express charging and discharging heat flows as well as losses (see $\kappa_{st,k}$ to the ambience with T_{amb}). The model as such is valid for time periods for on (i.e.: $\dot{m}_{sto} > 0$) as well as off-periods (i.e.: $\dot{m}_{sto} = 0$) of the storage pump.
Fig. 6 shows the validation of the storage tank for the charging period for on as well as the off storage pump periods. Three sensors are placed on the hull of the tank at distant locations.

D. Electric energy consumption of the actuating pumps

The predictive control concept proposed in this work takes into consideration the energy efficient operation of the actuat-

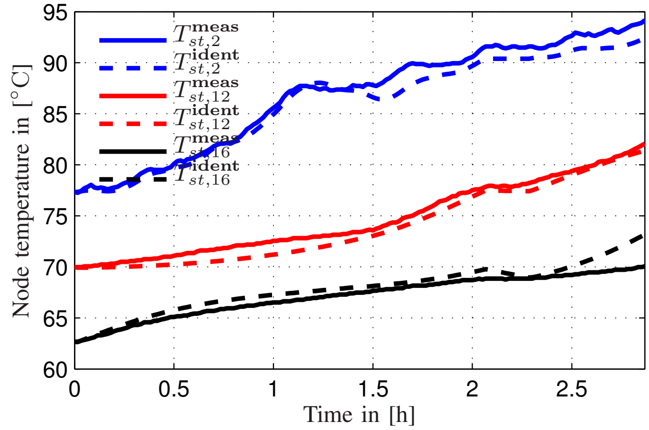

Fig. 6: Identification of stratified storage tank for nodes $k \in \{2, 12, 16\}$ during the charge period (i.e.: $\dot{m}_{sto} > 0$ and $\dot{m}_{load} = 0$) with $N = 20$.

ing pumps. Therefore, the model used to express the pumps' electric power consumption is given in Eq. (8).

$$P_{p,\{sol,sto\}} = \nu_{\{sol,sto\}} \dot{m}^3_{\{sol,sto\}} \tag{8}$$

The electric energy consumption is then given as the time integral of the consumed power, see Eq. (9).

$$\begin{aligned} E_{p,\{sol,sto\}} &= \int_{\tau_{on}}^{\tau_{off}} P_{p,\{sol,sto\}} \,\mathrm{d}t \\ &= \nu_{\{sol,sto\}} \int_{\tau_{on}}^{\tau_{off}} \dot{m}^3_{\{sol,sto\}} \,\mathrm{d}t \end{aligned} \tag{9}$$

where τ_{on} and τ_{off} denote the time instants at which the pumps are turned on and off respectively. $\nu_{\{sol,sto\}}$ is a pump-specific value. In this work it is identified using measurements for which the resulting curves represent the consumed electric power $P_{p,\{sol,sto\}}$ against the mass flow rates $\dot{m}_{\{sol,sto\}}$, see Fig. 7.

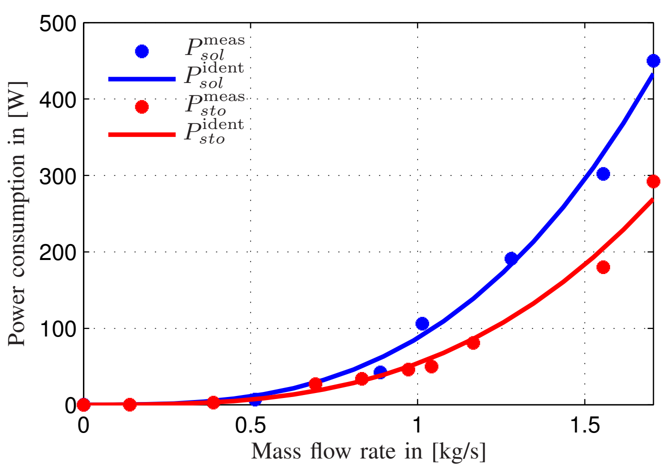

Fig. 7: Pump electric power consumption $P_{p,\{sol,sto\}}$ vs. mass flow rate $\dot{m}_{\{sol,sto\}}$.

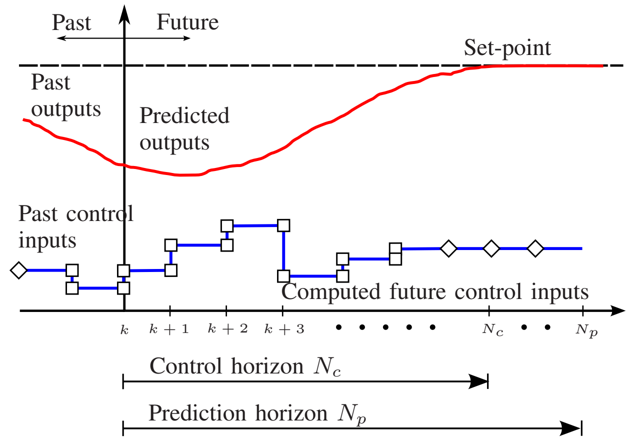

Fig. 8: The MPC principle [12].

III. Predictive Control Concept

In this section the model based predictive controller for the system depicted in Fig. 1 is designed. The basic principle of the model based predictive control approach is shown in Fig. 8. where at each time instant the optimal input trajectories are computed up to the control horizon N_c. For time instants $k \in [Nc + 1, Np]$ the control inputs are considered constant. Therefore, the system including Eq. (1), (3), (7) as well as the dead time approximation according to Eq. (6) is transformed in state space representation for the systematic controller design. The linear model predictive controller is derived on the basis of the discrete state space formulation from Eq. (10).

$$\begin{aligned} \mathbf{x}(k+1) &= \Theta \mathbf{x}(k) + \mathbf{\Omega} \mathbf{u}(k) + \mathbf{\Lambda} \boldsymbol{\omega}(k) \\ \mathbf{y}(k) &= C \mathbf{x}(k) \end{aligned} \tag{10}$$

where $\mathbf{x}(\mathbf{k})$ denotes the state vector with the temperatures from the equations Eq. (1), (3) and (7). The vector $\mathbf{u}(\mathbf{k})$ contains the manipulating variables $\dot{m}_{sol}$ and $\dot{m}_{sto}$. $\boldsymbol{\omega}_k$ comprises the disturbances $\left[G_t, T_{amb}, \dot{m}_{load}, T^{\text{load}}_{sup}, T^{\text{load}}_{ret}\right]$. The output vector includes the temperature differences (i.e.: $\mathbf{y} = [\Delta T_{sol}, \Delta T_{sto}]$) at the heat exchanger outlet of the solar as well storage circuit.
The control target is defined in accordance to the fact that maximal heat flow from the solar circuit $\dot{Q}_{sol} = \dot{m}_{sol} c_{sol} \Delta T_{sol} (\dot{m}_{sol})$ is achieved. The same applies to the storage circuit where $\dot{Q}_{sto} = \dot{m}_{sto} c_{sto} \Delta T_{sto} (\dot{m}_{sto})$ holds. As the temperature differences $\Delta T_{\{sol,sto\}}$ are dependent upon the corresponding mass flow rates $\dot{m}_{\{sol,sto\}}$, the control is stabilization of the desired temperature differences $\Delta T^*_{\{sol,sto\}}$.
The predictive control structure in this work includes a quadratic cost function J accounting for optimality with regards to energy consumption of the pumps as tracking control to minimize for the control error $\mathbf{e}(k) = \mathbf{y}^*(k) - \mathbf{y}(k)$ and therefore ensure an energy-efficient HVAC system operation, see Eq. (11).

$$\min_{\Delta \mathbf{u}} J := \sum_{i=0}^{N_p} \delta_y(i) \left[\mathbf{y}^*(k+i) - \mathbf{y}(k+i)\right]^2 \tag{11}$$

$$+ \sum_{i=0}^{N_c} \delta_u(i) \left[\mathbf{\Delta u}(k+i) + \mathbf{u}(k+i-1) \right]^2$$

subject to

$$\mathbf{u}_{min} \leq \mathbf{u}(k) \leq \mathbf{u}_{max}$$
$$\mathbf{\Delta u}_{min} \leq \mathbf{\Delta u}(k) \leq \mathbf{\Delta u}_{max}$$
$$\mathbf{y}_{min} \leq \mathbf{y}(k) \leq \mathbf{y}_{max}$$

Disturbance rejection is also considered by the predictive controller for which the control quality increases in the event that disturbances can be measured and predicted (i.e.: weather forecasts, known load profiles, etc.).
The cost function from Eq. (11) can be expressed in matrix notation (see Eq. (12)) thus giving possibility to compute the optimal input trajectories with less computational effort on the basis of a quadratic optimization problem.

$$J = (\mathbf{Y}^* - \mathbf{Y})^{\mathrm{T}} \boldsymbol{\lambda}_y (\mathbf{Y}^* - \mathbf{Y}) + (\mathbf{\Delta U} + \mathbf{U}_\pi)^{\mathrm{T}} \boldsymbol{\lambda}_u (\mathbf{\Delta U} + \mathbf{U}_\pi) \quad (12)$$

with the weighting factors λ_y and λ_u and the vectors

$$\begin{aligned}
\mathbf{Y}^* &= [\mathbf{y}^*(k_i), \mathbf{y}^*(k_i+1), \ldots, \mathbf{y}^*(k_i+N_p)] \quad (13)\\
\mathbf{Y} &= [\mathbf{y}(k_i), \mathbf{y}(k_i+1), \ldots, \mathbf{y}(k_i+N_p)]\\
\mathbf{\Delta U} &= [\Delta\mathbf{u}(k_i), \Delta\mathbf{u}(k_i+1), \ldots, \Delta\mathbf{u}(k_i+N_c-1)]\\
\mathbf{U}_\pi &= [\mathbf{u}(k_i-1), \mathbf{u}(k_i), \mathbf{u}(k_i+1), \ldots, \mathbf{u}(k_i+N_c-2)]
\end{aligned}$$

with the set-points, future outputs and future control inputs. The controller is implemented using the receding horizon principle where only the first input of the computed optimal input trajectory is applied to the plant.
More information about the systematic approach towards the design of the controller can be found in e.g.: [12].

IV. Simulation studies

In this section simulation studies are carried out to show the potential of the predictive control approach. The predictive control concept is hereby analyzed with regards to weather forecast information (i.e.: solar radiation and ambient temperature). This includes the optimal use of renewable energy source (e.g.: sun light) as well as the reduction of the electric energy consumption of the pumps. This approach is in accordance with the European Standard EN 15232 describing the impact of building automation, control systems on the energy efficient operation of buildings and HVAC systems. In the following simulation studies are carried out to show how energy efficiency can be increase using the model based predictive control concept within the frame of the solar powered HVAC system from Fig. 1. Simulation results incorporating the MPC approach are shown here in the event that the weather forecast is entirely correct[1]. The so obtained dynamic close loop behaviour is compared to the case where the weather forecast is supposedly misleading. Fig. 9 shows good tracking control as well as disturbance rejection by the MPC. In the case of non-correct weather data the control performance is not remarkably impacted. Fig.10 shows the corresponding control inputs $\dot{m}_{sol}$ and $\dot{m}_{sto}$. At time instant $k \approx 2.5h$ both

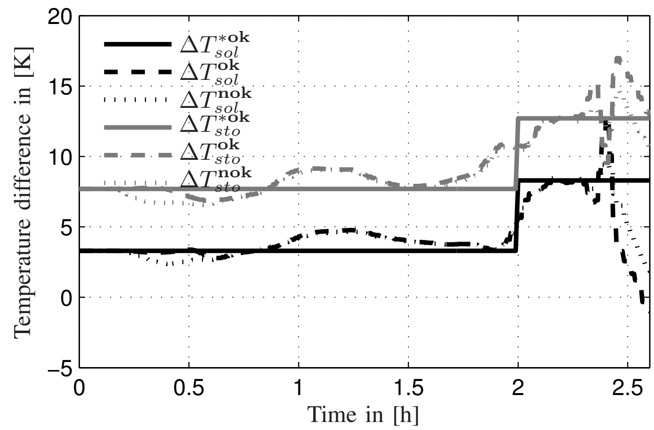

Fig. 9: Actual ΔT_{sol}^* vs. desired difference temperatures ΔT_{sol} and ΔT_{sto}^* for correct (superscript **ok**) and incorrect (superscript **nok**) weather data.

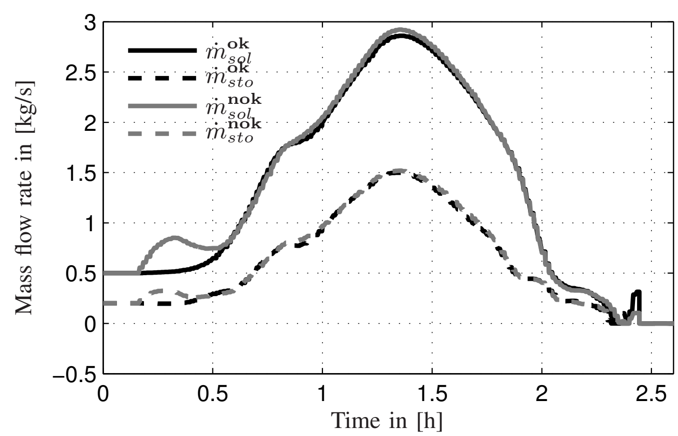

Fig. 10: Control inputs $\dot{m}_{sol}$ and $\dot{m}_{sto}$.

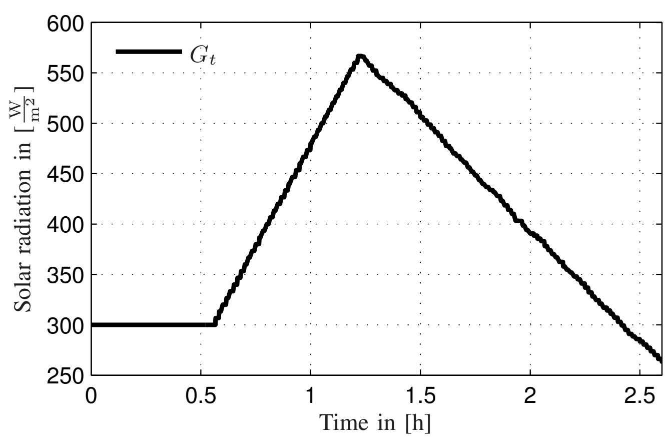

Fig. 11: Solar radiation G_t.

[1] This has only a theoretical meaning, as perfect forecast can never be expected.

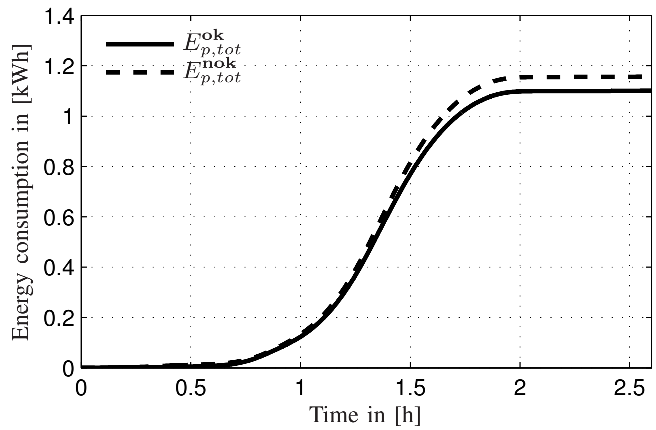

Fig. 12: Total energy consumption of the pumps in the solar and the storage circuit (i.e.: $E_{p,tot} = E_{p,sol} + E_{p,sto}$ using Eq. (9)).

pumps are turned off as a very low amount of solar radiation can be detected (i.e.: $< 300\ \frac{W}{m^2}$), see Fig. 11. This can further be see from Fig. 9 where the temperature differences ΔT_{sol} and ΔT_{sto} are decreasing rapidly. In order to allow for a transport of energy from the primary to the secondary circuit and therefore store it in the tank it would be necessary to decrease the mass flow rates in both circuits. However, as the predictive controller proposes control input trajectories tending to zero (see Fig. 10), it makes sense to turn off the pumps completely at this time instant. Fig. 12 shows further the overall energy consumption of the actuating pumps. Due to the slightly degraded performance being the consequence of incorrect weather data information, the energy consumption appears to be negligibly higher.

V. Conclusion

In this paper a predictive control concept for a solar powered HVAC system is introduced. The controller is based on dynamic models of HVAC components which were validated on the basis of measurements carried out on a real HVAC system. The excellent performance of the MPC approach is illustrated using weather forecast information where the MPC concept shows good performance even in the event that the weather forecast provides incorrect information. The receding horizon strategy of the MPC concept strictly accounts for such cases where the predicted information is not correct. The fact that constraints (e.g.: on control inputs, states, etc.) can be regarded systematically in the optimization problem improves the overall performance particularly with regards to the energy consumption of the actuators as saturation can be avoided. In contrast to that the conventional PID approach can suffer from control input saturation resulting in poor control and higher energy consumption (see e.g.: [12]). This negative effect is even more enhanced in the case that no anti-windup measures are included.

Further work will include the design of a nonlinear model predictive controller where the control target will not aim at the stabilization of temperature differences but on the maximization of the solar power gain from the solar circuit. The storage tank model will include a water feeder where the energy is fed into the layer with the temperature closest to the medium temperature of the heat exchanger outlet temperature in the storage circuit.

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