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Simulation and Control of Solar Thermal Power Plants

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Abstract. In this paper, first the overall modeling approach for an optimized control of a hot-gas cycle for solar thermal power plants in the Modelica language is pointed out. The emphasis of the modeling work lies on the development of dynamic component models to be used in control systems. Depending on the control task, the discretization of the models has to be adapted. Main components of the hot-gas cycle are the solar thermal receiver and the storage system. The steam cycle is preliminarily only included as heat sink.

Second, for control purposes a linear model-based controller (MPC) was implemented in Modelica based on an external state-of-the-art QP solver [2] linked to the Modelica model. The performance of the MPC is compared with a basic automation scheme based on classical PID controllers.

Key words

Solar energy, modeling, control, optimization

1. Introduction

One possible answer to address climate change is using solar instead of fossil energy. Among other technologies central receiver systems (CRS) using air as heat transfer medium are being investigated. A demonstration plant in Jülich, Germany (Solarthermisches Versuchskraftwerk Jülich, STJ) has just been completed [8].

The STJ uses 18000 m² of sun-tracking mirrors (heliostats) to heat air up to 700 °C which in turn generates superheated steam, driving a turbine and generator. A storage system can take up the thermal energy for one full-load hour. By adjusting the rate of the volume flow of two blowers, it is possible to charge or discharge the storage during operation.

The Virtual Institute of Central Receiver Power Plants (vICERP) has been founded to solve the demanding requirements for the optimal plant control under the strongly fluctuating energy input.

2. Modeling

For the modeling of the plant with its different components the Modelica language has been chosen, which is well suited for modeling thermo-hydraulic systems. Furthermore, Dymola is used as development and simulation environment.

The modeling efforts are shared among the vICERP partner institutions. Therefore, it is crucial to use a common model setup to ensure a proper use of the models. A common test platform provides the necessary interfaces, so that new, improved modules can easily be integrated and tested. The models are based on the Modelica Fluid library [1]. The vICERP library uses a finite volume approach with staggered grid method implemented with flow and volumes elements. The mass and energy balances are considered in the volume element. A formulation of the balance equations from Hirsch [4] is implemented using pressure and specific enthalpy as state variables. The momentum equation is reduced to a pressure drop equation and formulated in a flow element.

Fig. 1 shows the top-level of the model developed in Dymola/Modelica. Several different components can be identified in the figure: the heliostat field and receiver on the top left, the storage in the middle, a simple model of the water steam cycle on the right and the two blowers on the bottom right. The following sections give a brief introduction to the models.

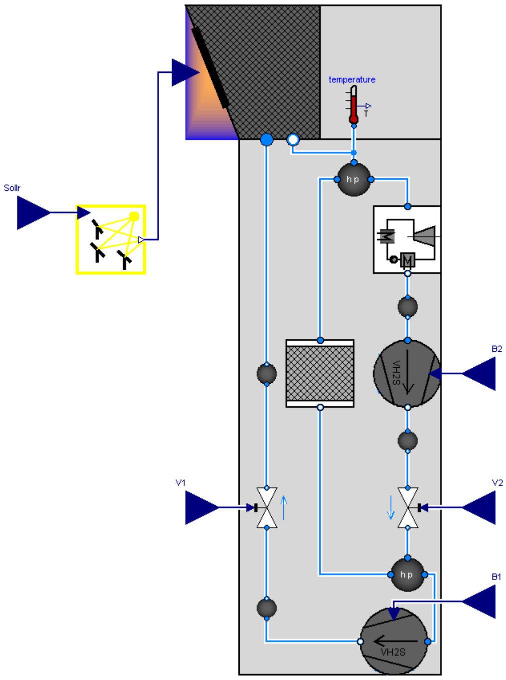

Fig. 1. Screenshot of the model in Dymola

A. *Heliostat field and receiver*

The 2200 heliostats that focus the sunlight onto the receiver are calculated by a special Monte-Carlo ray-tracing code, called STRAL [7], which generates a flux map on a surface which coincides with the receiver. The receiver is modeled in Modelica. The output is an averaged temperature for the air mass flow entering the hot-gas system.

In the STJ, an open volumetric air receiver is installed which uses ambient air sucked through a hot porous volumetric absorber, where the air is heated up.

B. *Hot-Air Pipes and Blowers*

The models for hot-air pipes are simplified using one volume and one flow element for each pipe. The blower models include the characteristic curve of the blower provided by the manufacturer. Implemented in a lookup table, this map allows the calculation of a resulting mass flow given the power input and pressure difference between inlet and outlet port of the blower.

C. *Storage*

A thermal storage system is used as a buffer that stores energy at times of high irradiances and enables operation of the plant after sunset or during periods of reduced solar input. The developed storage model enables the analysis of different operation conditions of the power plant. The storage behavior is similar to that of a regenerator. The hot air flows through the storage material and heats it up. During discharge, the air flows in reverse direction and cools down the storage material, while being heated up.

The storage model is divided into storage cells. Each cell element describes the characteristic material and flow phenomena, which are included in differential equations. Thus, each cell element computes two temperatures which represent the local temperature of the storage material and the local temperature of the fluid. In the energy equation convection between the material and the gas fluid and conduction inside the storage material in two dimensions are considered.

The model enables the description of charging, discharging and stand-by operation. Additionally, heat losses during stand-by periods are calculated. Thus, temperature profiles inside the storage can be computed for any time in the simulation process. Fig. 2 shows the temperature profile for the 100%- and 0%-storage capacity load situation.

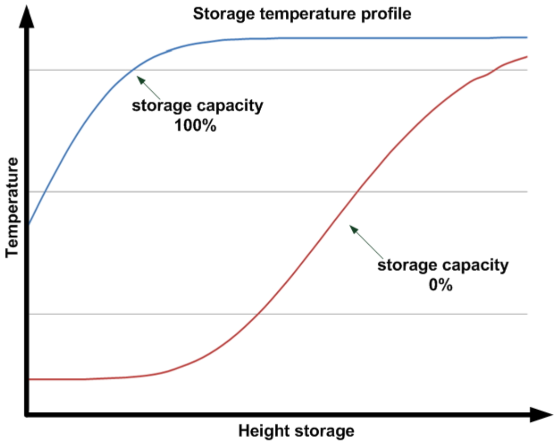

Fig. 2. Tempearture profile of the storage for 100%- and 0%-storage load

D. *Water Steam Cycle*

Whereas in the final system the steam cycle will be modeled in detail, it is – at this stage – merely integrated as a heat sink, featuring qualitatively the steam cycle's anticipated behavior

3. Control

A. *Basic automation scheme*

The simulation of the operational behavior of the complete plant requires an integrated control scheme within the model to ensure compliance with given limits of absolute and gradient values. As a first concept, a basic automation scheme has been developed based on a wiring of SISO control loops with PID controllers. This scheme should on one hand assure a safe operation of the plant under normal operation conditions and on the other hand be a measure of performance for more sophisticated control schemes.

The tuning of the different controllers has been done in MATLAB using a response optimization technique. An extract of the scheme is depicted in Fig. 3.

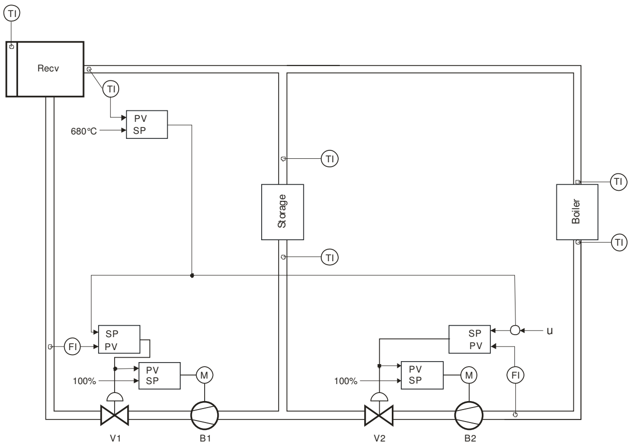

Fig. 3. Basic automation scheme

The measurement signals for the control scheme are different volume flows and temperature information. Actuating variables are the speed of the two blowers and different valves located in the air cycle.

The main goal of the control scheme is to maintain the outlet air temperature of the receiver constant at 680 °C. This is achieved by controlling the air volume flow through the receiver. As a consequence of an increasing volume flow through the receiver, the temperature of the outgoing air decreases.

The temperature difference from the reference point is used in an outer control loop of a cascaded structure, which feeds the required volume flow as setpoint to the inner control loop.

The inner loop accesses two actuators for adjusting the volume flow, a blower and a valve mounted directly after the blower. The blower is obviously necessary to generate the air flow. The use of the valve is necessary for two reasons. First, the blower itself has a low pressure drop during standstill periods such that an airstream just flows through it if the stream is generated by the other blower installed in series. Second, the blower is limited to a minimal rotational speed. Therefore, the valve is closed appropriately to set volume flows below the threshold given by the blower itself.

B. Model predictive control

The vICERP project includes the application of a *model predictive controller (MPC)*. This approach makes use of the dynamic model of the plant that has been developed for the simulation to predict future behavior with respect to changes in actuating variables.

With an MPC approach, it is also possible to include a natural objective function (maximize produced energy, minimize risk of boiler shutdown during transients, minimize time to start-up etc.) as well as imposing constraints such as bounds on variables or periodicity constraints.

The investigated MPC controller is based on a linear state space model of the form:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{1}$$

Up to now, only a *linear* model predictive controller is taken into account. However, the project aims at using the full *nonlinear* model of the plant to find optimal control actions.

Based on the above representation the controller is able to predict the future behaviour of the plant using a future trajectory for the input (and possible disturbances). This can be expressed in an equation of the form

$$\begin{aligned} &\hat{Y}(k) = \\ &\Psi \cdot x(k) + \Upsilon \cdot u(k-1) + \Theta \cdot \Delta U(k) + \Xi \cdot D_m(k) \end{aligned} \tag{2}$$

with suitable matrices Ψ, Υ, Θ and Ξ at time k [5]. The different terms represent the free and forced response of the plant, together with the response to future trajectories of the inputs and measured disturbances. Combined with a given reference trajectory for the outputs and additional linear constraints on the states and inputs, this can be reformulated as an optimization problem of the form

$$\min_{\Delta U(k)} \Delta U(k)^T \cdot H \cdot \Delta U(k) - g^T \cdot \Delta U(k) \tag{3}$$

with Hessian matrix H and gradient vector g. This is a standard optimization problem known as the *Quadratic Programming (QP)* problem.

The MPC controller requires the above quadratic program to be solved at each sampling time. This is carried out with the QP solver qpOASES [2], which uses an online active-set method particularly suited for MPC problems [3].

C. Additional feed-forward control

The main difference between the control of a conventional compared to a solar plant is that the energy input in the first case is an actuating variable, whereas in the second case it (the solar irradiation) acts as a disturbance.

However, this disturbance is not completely random, but may be measurable or even predictable (e. g. by weather forecast or vision based [6]). This information can also be included in the different controllers. For the basic automation scheme this has been accomplished by adding a nonlinear feed-forward control based on a Hammerstein-model as depicted in Fig. 4.

This model calculates from a given solar irradiation the necessary air volume flow through the receiver which results in the desired air outlet temperature.

In case of the MPC, it is straightforward to include the solar irradiation by using it also in the prediction of the plant output.

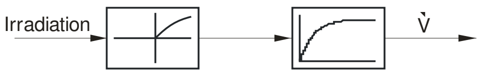

Fig. 4. Hammerstein-model for feed-forward control

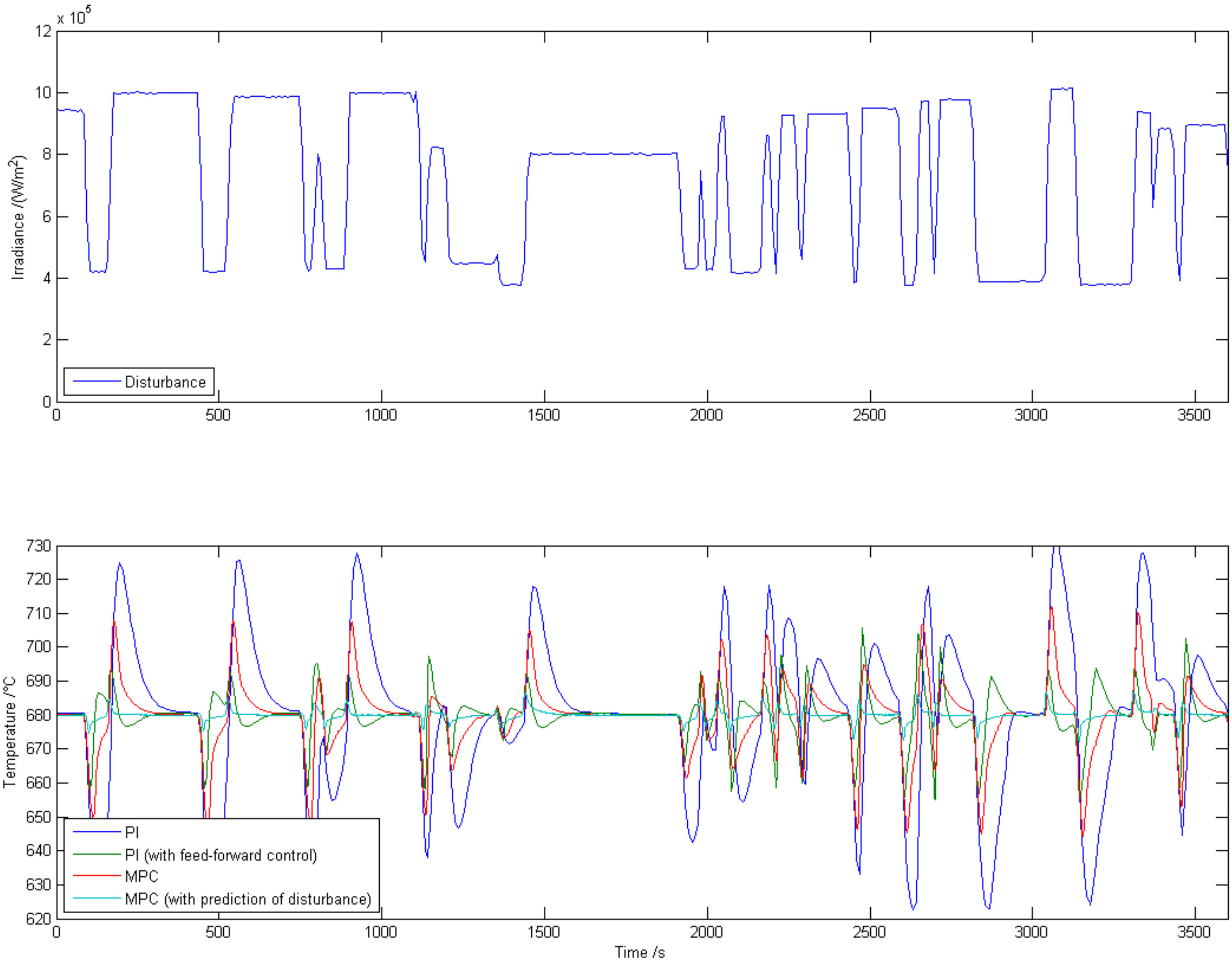

Fig. 5. Simulation results

4. Simulation Results

Due to the lack of measurement data, a stochastic test signal for the solar irradiance based on the model given in [9] overlaid with small-scale fluctuations [10] is used for evaluation of the model and different control schemes. The test signal is depicted in the upper part of Fig. 5. Although the direct radiation may drop to zero if the heliostat field is completely covered with clouds, the above signal is used since a comparison of the different control schemes would not be particularly significant if all schemes run into their lower saturation during periods with no direct radiation. The parameterization for the model generating the test signal was chosen in such a way that the control schemes probably saturate during periods with low irradiation.

In the lower part of Fig. 5 the responses of the air outlet temperature at the receiver with the different controllers are depicted. The main goal of this feedback control is disturbance rejection, i. e. it should assure a constant outlet temperature by adjusting the air volume flow through the receiver appropriately.

The first case in blue shows the resulting characteristics if the control scheme as depicted in Fig. 3 based on PID controllers is used. The second curve depicted in green shows the response of the outlet temperature if the feed-forward control as described above (cf. Fig. 4) is added to the scheme.

In the following two cases the implemented MPC was used to control the air temperature. Therefore, the PI controller in Fig. 3 which uses the air temperature as measurement variable in the outer control loop was replaced by an MPC-block. The inner controllers directly manipulating the actors remain the same. Although the model-based controller has inherently the ability to cope with systems with multiple in- and outputs, in this case it is just used with a single in- and output. In the last case depicted in cyan, the MPC-block was extended to also incorporate the influence of the disturbance on the system by feed-forward control.

As one can see, the model-based controller achieves superior performance compared to the scheme based on PID controllers in both cases, i. e. if the additional knowledge about the actual or future solar irradiation is taken into account or not. However, this knowledge does improve the quality of both controllers tremendously. Also note that especially the PI controller suffers from the all-pass behavior of the receiver regarding steps in the volume flow. Thus, the adjustment of the controller parameters is always a trade off between responsiveness and the maximal overshoot of the temperature.

5. Conclusion

In this paper we have presented a first-principle model for a central receiver solar power plant with open volumetric receiver. The model includes the different components of the plant, e. g. receiver, storage, and is used for simulation and optimization purposes of both the separate components and also the plant behavior as a whole.

For control purposes a linear model-based controller (MPC) was implemented and achieves good performance. The implementation is based on an external state-of-the-art QP solver linked to the Modelica model for the calculation of optimal control actions.

Future work aims at not only using optimal control for the air cycle as presented in this paper, but also to extend this approach to other areas of the plant, e. g. storage regulation. It can be forseen that the MPC is better suited to comply with given constraints in these cases.

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