SMART ADAPTIVE CONTROL OF A SOLAR THERMAL POWER PLANT IN VARYING OPERATING CONDITIONS

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ABSTRACT

Solar thermal power plants collect available solar energy in a usable form at a temperature range which is adapted to the irradiation levels and seasonal variations. Solar energy can be collected only when the irradiation is high enough to produce the required temperatures. During the operation, a trade-off of the temperature and the flow is needed to achieve a good level for the collected power. The storage is needed to keep the heat supply during the nights and heavy cloudy periods. Efficient operation requires a fast start-up and reliable operation in cloudy conditions without unnecessary shutdowns and start-ups. Fast and well damped linguistic equation (LE) controllers have been tested in Spain at a collector field, which uses parabolic-trough collectors to supply thermal energy in form of hot oil to an electricity generation system or a multi-effect desalination plant. Control is achieved by means of varying the flow pumped through the pipes in the field during the operation. The LE controllers extend the operation to varying cloudy conditions in a smart way. Varying irradiation and energy demand during the daytime can be smoothly handled in the LE control system with predefined model-based adaptation techniques. The system activates special features when needed to facilitate smooth operation. The intelligent state indicators react well to the changing operating conditions and can be used in smart working point control to further improve the operation in connection with the other energy sources.
Keywords: Solar energy, intelligent control, nonlinear systems, adaptation, optimisation, linguistic equations, modelling, simulation

INTRODUCTION

Solar power plants should collect any available thermal energy in a usable form at the desired temperature range, which improves the overall system efficiency and reduces the demands placed on auxiliary equipment. In addition to seasonal and daily cyclic variations, the intensity depends also on atmospheric conditions such as cloud cover, humidity, and air transparency. A fast start-up and efficient operation in varying cloudy conditions is important. A solar collector field is a good test platform for control methodologies [1, 2, 3]. Model-based approaches are useful since the operation depends strongly on weather conditions: the model structure is fairly clear but the properties of the oil depend on the temperature [4]. Lumped parameter models taking into account the sun position, the field geometry, the mirror reflectivity, the solar irradiation and the inlet oil temperature have been developed for a solar collector field [1]. A feedforward controller has been combined with different feedback controllers [5]. Local linearization has been used in feedback control [6]. Feedforward approaches based directly on the energy balance can use the measurements of solar irradiation and inlet temperature [7]. Energy collection is focused in [8]. Model-based predictive control [9, 10] is suitable for fairly smoothly changing conditions. The classical internal model control (IMC) can operate efficiently in varying time delay conditions [11]. Genetic algorithms have also been

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used for multiobjective tuning [12].
Linguistic equation (LE) controllers use model-based adaptation and feedforward features, which are aimed for preventing overheating, and the controller presented in [13] already took care of the actual setpoints of the temperature. The manual adjustment of the working point limit has improved the operation considerably. Parameters of the LE controllers were first defined manually, and later tuned with neural networks and genetic algorithms. Genetic algorithms combined with simulation and model-based predictive control have further reduced temperature differences between collector loops [14]. Data analysis methods are based on generalised norms [15] and extended to a recursive version of the scaling approach was introduced in [16]. New state indicators for detecting cloudy conditions and other oscillatory situations by analysing fluctuations of irradiation, temperature and oil flow [17]. The new indicators react well to the changing operating conditions and can be used in smart working point control. Recent developments include advanced model-based LE control are discussed in [18] and intelligent analysers [19].
This paper summarises and analyses the overall operation of the LE controller in changing operating conditions. The analysis is based on experiments carried out in the *Acurex Solar Collectors Field of the Plataforma Solar de Almeria (PSA)* in Spain.

SOLAR COLLECTOR FIELD

The aim of solar thermal power plants is to provide thermal energy for use in an industrial process such as seawater desalination or electricity generation. Unnecessary shutdowns and start-ups of the collector field are both wasteful and time consuming. With fast and well damped controllers, the plant can be operated close to the design limits thereby improving the productivity of the plant [4].
The *Acurex field* supplies thermal energy (1 MW_t) in form of hot oil to an electricity generation system or a multi–effect desalination plant. Parabolic–trough collectors are used for focusing the irradiation on the pipes and control is achieved by means of varying the flow pumped through the pipes (Fig. 1) during the operation. In addition to this, the collector field status must be monitored to prevent potentially hazardous situations, e.g. oil temperatures greater than 300 ^oC. The temperature increase in the field may

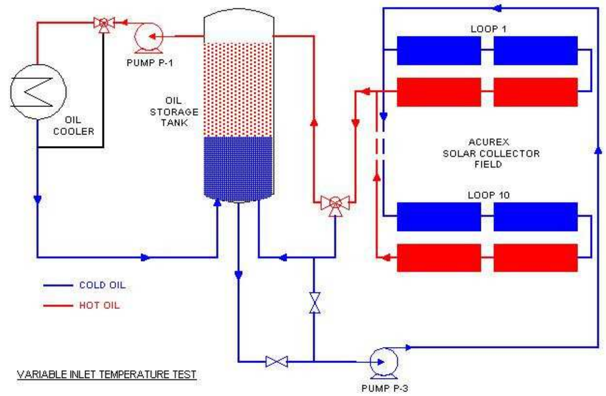


Figure 1: Layout of the Acurex solar collector field.

rise up to 110 degrees. At the beginning of the daily operation, the oil is circulated in the field, and the flow is turned to the storage system (Fig. 1) when an appropriate outlet temperature is achieved. The valves are used only for open-close operation: the overall flow F to the collector field is controlled by the pump. [20] The latest test campaigns focused on achieving a smooth operation in changing operating conditions to avoid unnecessary stress on the process equipment.

SMART ADAPTIVE CONTROL

The multilevel control system consists of a nonlinear PI-type LE controller with predefined adaptation models, some smart features for avoiding difficult operating conditions and a cascade controller for obtaining smooth operation (Fig. 2). Controller performance is used in the adaptation module. For the solar collector field, the goal is to reach the nominal operating temperature $180 - 295\ ^oC$ and keep it in changing operating conditions [16, 17]. The feedback controller is a PI-type LE controller with one manipulating variable, oil flow, and one controlled variable, the maximum outlet temperature of the loops. The controller provides a compact basis for advanced extensions. High-level control is aimed for manual activating, weighting and closing different actions.

Feedback LE controller

Feedback linguistic equation (LE) controllers use error $e_j(k)$ and derivative of the error $\Delta e_j(k)$. These real values are mapped to the linguistic range $[-2, 2]$

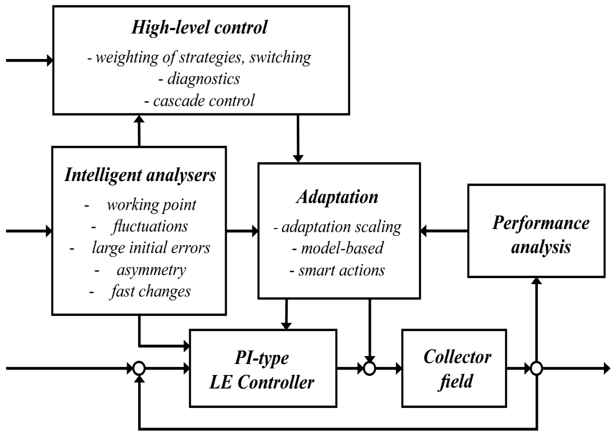


Figure 2: LE controller of the Acurex solar collector field.

by nonlinear scaling with variable specific membership definitions (f_e) and $f_{\Delta e})$, respectively. As all these functions consist of two second order polynomials, the corresponding inverse functions consist of square root functions. The linguistic values of the inputs, $\widetilde{e_j(k)}$ and $\Delta\widetilde{e_j(k)}$, are limited to the range $[-2,2]$ by using the functions only in the operating range: outside the scaled values are -2 and 2 for low and high values, respectively.

A *PI-type LE controller* is represented by

$$\Delta\widetilde{u_{ij}(k)} = K_P(i,j)\,\Delta\widetilde{e_j(k)} + K_I(i,j)\,\widetilde{e_j(k)}, \qquad (1)$$

which contains coefficients $K_P(i,j)$ and $K_I(i,j)$. The effects of $\widetilde{e_j(k)}$ and $\Delta\widetilde{e_j(k)}$ can be tuned by membership definitions $(f_e)_j$ and $(f_{\Delta e})_j$, respectively. However, the direction of the control action is fixed in (1). Different directions and strengths can be handled with this controller.

The output i of a single input single output (SISO) controller is calculated by adding the effect of the controlled variable j to the manipulated variable i:

$$u_i(k) = u_i(k-1) + \Delta u_{ij}(k). \qquad (2)$$

In the PI-type LE controller, the error variable is the deviation of the outlet temperature from the set point, and the control variable is oil flow.

Intelligent analysers

Intelligent analyzers are used for detecting changes in operating conditions to activate adaptation and model-based control and to provide indirect measurements for the high-level control. The data analysis is based on the generalised norms

$$||^{\tau}M_j^p||_p = (^{\tau}M_j^p)^{1/p} = [\frac{1}{N}\sum_{i=1}^{N}(x_j)_i^p]^{1/p}, \qquad (3)$$

where $p \neq 0$, is calculated from N values of a sample, τ is the sample time. These norms can be calculated recursively [16].

Working point On a clear day, the field could be operated by selecting a suitable a balance between the irradiation and the requested temperature increase. The *working point* is represented by

$$wp = \tilde{I}_{eff} - \tilde{T}_{diff}, \qquad (4)$$

where $\tilde{I}_{eff}$ and $\tilde{T}_{diff}$ are obtained by the nonlinear scaling of variables: efficient irradiation I_{eff} and temperature difference between the inlet and outlet, $T_{diff} = T_{out} - T_{in}$. The outlet temperature T_{out} is the maximum outlet temperature of the loops. This model handles the nonlinear effects: the volumetric heat capacity increases very fast in the start-up stage but later remains almost constant because the normal operating temperature range is fairly narrow.

The working point variables already define the overall normal behaviour of the solar collector field, $wp = 0$, where the irradiation $\tilde{I}_{eff}$ and the temperature difference, $\tilde{T}_{diff}$, are on the same level. A high working point $(wp > 0)$ means low $\tilde{T}_{diff}$ compared with the irradiation level $\tilde{I}_{eff}$. Correspondingly, a low working point $(wp < 0)$ means high $\tilde{T}_{diff}$ compared to the irradiation level $\tilde{I}_{eff}$. The normal limit $(wp_{min} = 0)$ reduces oscillations by using slightly lower setpoints during heavy cloudy periods. Higher limits, e.g. $(wp_{min} = 1)$, shorten the oscillation periods after clouds more efficiently.

Fluctuations The *fluctuation indicators*, which were introduced to detecting cloudiness and oscillations, are important improvements aimed for practical use. The cloudy conditions are detected by calculating the difference of the high and the low values of the corrected irradiation as a difference of two moving generalised norms:

$$\Delta x_j^F(k) = ||^{K_s\tau}M_j^{p_h}||_{p_h} - ||^{K_s\tau}M_j^{p_l}||_{p_l}, \qquad (5)$$

where the orders $p_h \in \Re$ and $p_l \in \Re$ are large positive and negative, respectively. The moments are calculated from the latest K_s+1 values, and an average of several latest values of $\Delta x_j^F(k)$ is used as an indicator of fluctuations. [17]

Large initial errors Large steps and irradiation disturbances may cause very large initial errors which are detected by the *predictive braking indication*. The calculated braking coefficient, $bc_j(k)$ is used to emphasise the influence of the derivative of the error by means of the following equation:

$$K_P(i,j) = (1+bc_j(k))\, K_P(i,j) \qquad (6)$$

A new solution has been introduced to detecting the large error.

Asymmetry The control surface should be asymmetric when the irradiation is strongly increasing or decreasing. The *asymmetry detection* is based on the changes of the corrected irradiation. The action is activated only close to the set point if there are no strong fluctuations of the controlled variable evaluated by e_j^- and e_j^+. The previous calculation based on the solar noon does not take into account actual irradiation changes.

Fast changes Fast changes may occur in the temperatures (inlet, outlet and difference). Changes of the inlet temperature have a strong effect on the outlet temperature. The change is detected with the index

$$\Delta T_{in}^H(k) = T_{in}(k) - \frac{1}{n_L+1}\sum_{i=k-n_L}^{k} T_{in}(i), \qquad (7)$$

where the average value is calculated from n_L+1. A smooth increase is normal during the daily operation and strong effects are detected after load disturbances.

Fast changes of the outlet temperatures were considerably reduced when the fluctuation indicators were taken into use to adapt the setpoint. Too fast outlet temperature increase represented by the value range $\Delta T_{out}^R(k)$ obtained as the difference of maximum and minimum values of $T_{out}(i)$ in the range $i=k-n_L,\ldots,k$. This index is activated if T_{out} has increased during the period. An indicator of too high temperature differences is based on the detection of an overshoot

$$\Delta T_{out}^H(k) = \max\{0, T_{out}(k) - T_{out}^{sp}\}. \qquad (8)$$

Adaptive control

Adaptive LE control extends the operating area of the LE controller by using correction factors obtained from the working point (4) to reduce oscillations, when wp is low, and to speedup operation, when wp is high. This predefined adaptation is highly important since there are not time enough to adapt online when there are strong disturbances.

The predictive braking and asymmetrical actions are activated when needed. Intelligent indicators introduce additional changes of control if needed. The test campaigns have clarified the events, which activate the special actions. Each action has a clear task in the overall control system.

The additional intelligent features $\Delta T_{in}^H(k)$, $T_{out}^R(k)$ and $\Delta T_{out}^H(k)$, which detect anomalies, introduce an additional change of control:

$$\Delta \widetilde{u_j^{CH}}(k) = c_1 \Delta \widetilde{T_{in}^H}(k) + c_2 \widetilde{T_{out}^R}(k) + c_3 \Delta \widetilde{T_{out}^H}(k), \qquad (9)$$

where the coefficients c_1, c_2 and c_3 are chosen from the range [0, 1]. The first two actions are predictive, and the third one is corrective. If T_{diff} is too high, also the set point is corrected correspondingly to avoid low working point $wp_i(k) \ll 0$.

Model-based control

Model-based control was earlier used for limiting the acceptable range of the temperature setpoint by setting a lower limit of the working point (4). The fluctuation indicators are used for modifying the lower working point limit to react better to cloudiness and other disturbances. This overrides the manual limits if the operation conditions require that.

The model-based extension is an essential part in moving towards reliable operation in cloudy conditions: the control system can operate without manual interventions. The high-level control moves towards control strategies to modify intelligent analysers and adaptation procedures (Fig. 2).

RESULTS

The control system was tested on a solar collector field at PSA in July 2012 to find a suitable solution for sustainable almost unattended operation. The results are used in developing optimisation solutions for the energy collection.

Normal operation

On clear days with high or fairly high irradiation, the setpoint tracking is acceptable: step changes from 15-25 degrees are achieved in 20-30 minutes with minimal oscillation. The working point adaptation operates efficiently and the temperature can be increased and decreased in spite of the irradiation changes (Fig. 3).

High setpoints can be used since the working point limit activates the setpoint correction when the temperature difference exceeds the limit corresponding to the irradiation level in the active working point level. There are three time periods of reduced setpoints in Figure 3 from 11:40 to 12:18, from 12:50 to 13:30 and from 14:48 to 15:40.

The oil flow changes smoothly: the fast changes are at the beginning of the step (Fig. 4). Working point corrections and limiting the fast changes are negligible. The predictive braking was activated in these situations, but the asymmerical action was not yet available. This causes positive offset, when the irradiation is increasing before the solar noon. Correspondingly, the offset is negative after the solar noon.

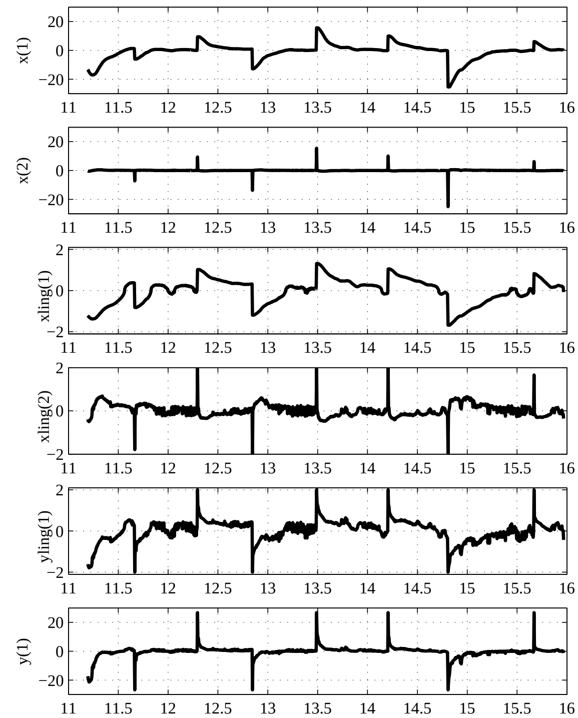


Figure 4: Operation of the LE controller on a fairly clear day: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

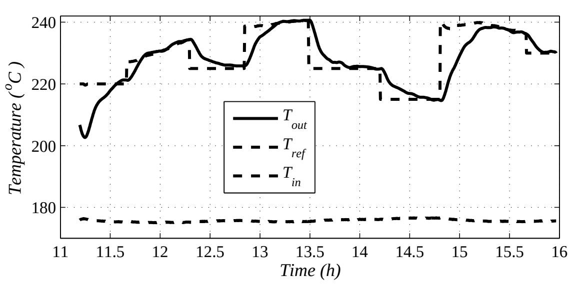


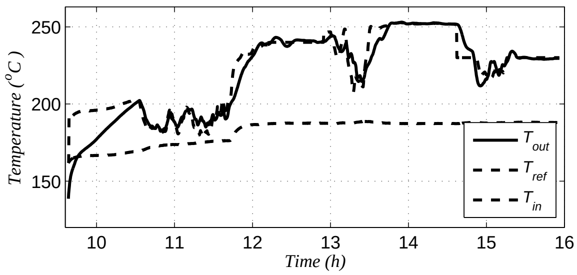
Figure 3: Test results of the LE controller on a fairly clear day [19].

Cloudy conditions

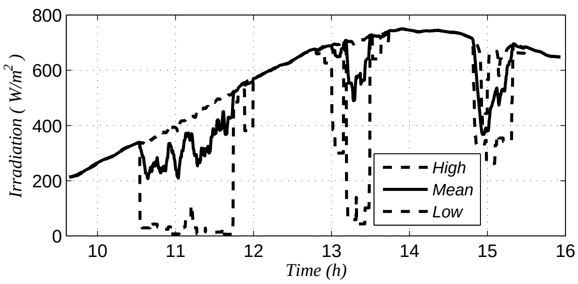
The setpoint correction operates throughout the cloudy periods to reduce oscillations and hazardous situations caused by the abrupt changes of irradiation (Fig. 5(b)).

Three cloudy periods occurred on the third day: a long period in the morning, a short light one close the solar noon and a short, but heavy, in the afternoon. The temporary setpoint correction operated well in these situations (Fig. 5(a)). During the cloudy periods (Fig. 5(b)), the temperature went down with 20 degrees but rose back during the short sunny spells, and finally, after the irradiation disturbances, high temperatures were achieved almost without oscillations with the gradually changing setpoint defined by the working point limit although the inlet temperature was simultaneously rising. After these periods, the field reached the normal operation in half an hour.

The controller used high oil flow levels when the sky was clearing up. Also the change of control was reacting strongly (Fig. 6). The same approach operated well for the other two cloudy periods. The oil flow was changed smoothly also during these periods. The working point corrections were now very strong, but limiting the fast changes was hardly needed. Strong braking was used in the beginning and in the recovery from the first cloudy period. There were problems with some loops during that day.



(a) Outlet temperature.



(b) Irradiation.

Figure 5: Test results of the LE controller on a cloudy day [19].

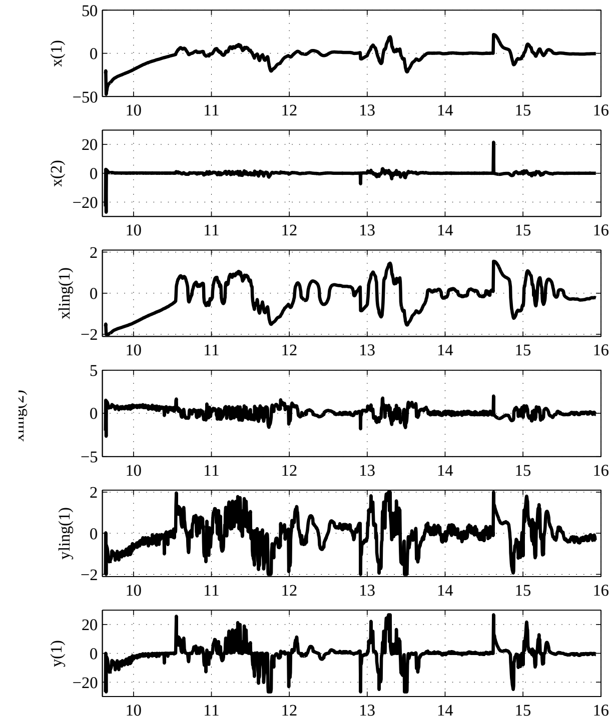


Figure 6: Operation of the LE controller on a cloudy day: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

The fourth day had two very different periods: the start was very bright and the irradiation was rising smoothly, but everything was changed just before the solar noon, and the heavy cloudy period continued the whole afternoon. The field was in temperatures 160 - 210 ^oC for more than two hours although the loops were not tracking the sun all the time. The working point corrections were during this period very strong, but limiting the fast changes was hardly needed [18].

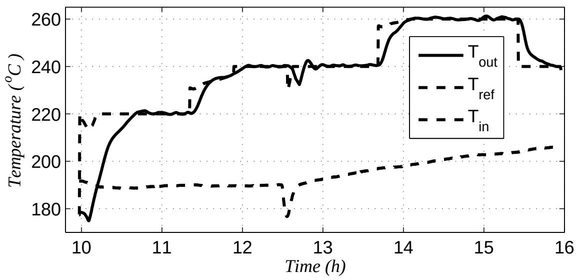
Load disturbances

During a day, the temperature increases more or less smoothly in the storage tank (Fig. 1), but the use energy may cause fast disturbances. The controller should also hande these disturbances. On the fifth day, the start-up followed the setpoint defined by the working point limit. In addition, there was an unintentional drop of 16.9 degrees in the inlet temperature. The disturbance lasted 20 minutes. The controller reacted by introducing a setpoint decrease of 19.8 degrees. The normal operation was retained in 50 minutes with only an overshoot of two degrees, but with some oscillations.

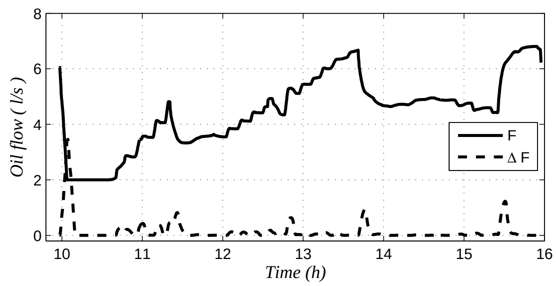
This kind of disturbance was repeated on the sixth day (Fig. 7(a)): the inlet temperature was dropped maximum 13.5 degrees during a period of 15 minutes. Now the setpoint was changed when the inlet temperature reached the minimum. The working point limit was changed to allow a higher setpoint in the recovery. The change of control is operating in a similar way as in the setpoint change (Fig. 8). The temperature drop was smaller (7.5 degrees) but the overshoot slightly higher (2.5 degrees). Also the recovery took less time (30 minutes).

Asymmetrical correction

The new asymmetrical correction was activated in several periods on the sixth day. There were good results on two previous days, but now the operation was better tuned for the afternoon as well. The setpoints were achieved in the range $\pm$ 0.5 degrees with hardly any offset (Fig. 7(a)). The change is considerable to the first days, when the outlet tempera-



(a) Outlet temperature.



(b) Oil flow.

Figure 7: Test results of the LE controller on a clear day: asymmetral action [19,].

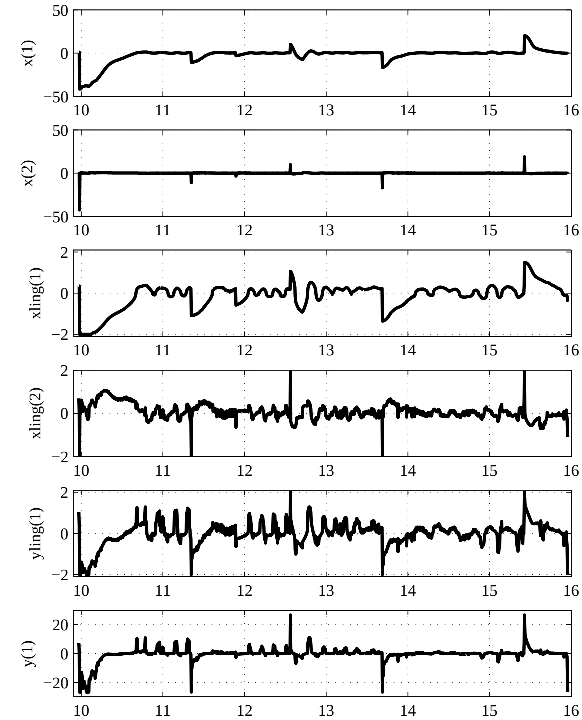


Figure 8: Operation of the LE controller on a clear day, including asymmetry action: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

ture exceeded the setpoint with 0.5-1 degrees, when the irradiation was increasing, and remained about 1.0 degrees lower when the irradiation decreased. Around the solar noon, the setpoint was achieved very accurately even for high temperatures corresponding negative working points. The increase of the inlet temperature is smoothly compensated with small changes of the oil flow and the setpoint is also accurately achieved after the load disturbance (Fig. 7(b)). In this case, the asymmetrical action increases the positive changes before the solar noon and the negative changes after that (Fig. 8).

Optimisation

The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon. As the inlet temperature often increases slightly during the day, there is a possibility to use even higher outlet temperatures. The temperatures increase with decreasing oil flow, which can be controlled smoothly in a wide range. A trade-off of the temperature and the flow is needed to achieve a good level for the collected power. The working point is chosen from the high power range and used in the model-based control to choose or limit the setpoint. The power surface is highly nonlinear because of the properties of the oil. Disturbances of the inlet temperatures introduce fluctuation to the outlet temperature (Fig. 7(a)). The acceptable working point is limited by the oscillation risks and high viscosity of the oil during the start-up. In the latest tests, the inlet temperatures are high already in the start-up, since the oil flow was not first circulated in the field. During high irradiation periods, high outlet temperatures are avoided by keeping the working point high enough.

CONCLUSION

The intelligent LE control system, which is based on intelligent analysers and predefined model-based adaptation techniques, activates special features when needed. Fast start-up, smooth operation and efficient energy collection is achieved even in varying operating condition. The state indicators react well to the changing operating conditions and can be used in smart working point control to further improve the operation. The controller reacts efficiently on the setpoint changes, clouds and load disturbances. The setpoint is achieved accurately with the new asymmetrical action. The working point can be chosen in a way which improves the efficiency of the energy collection. A trade-off of the temperature and the flow is needed to achieve a good level for the collected power.

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