Intelligent Control of a Solar Thermal Power Plant - Adaption in Varying 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 intelligent control system based on intelligent analyzers and predefined adaptation techniques activates special features when needed. Fast start-up, smooth operation and efficient energy collection is achieved even in variable 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 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.**

Keywords-solar energy, intelligent control, nonlinear systems, adaptation, optimisation

I. INTRODUCTION

Solar thermal power plants should collect any available energy in a usable form at the desired temperature range. 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], including basic feedforward and PID schemes, adaptive control, model-based predictive control, frequency domain and robust optimal control and fuzzy logic control [4].

Feedforward approaches based directly on the energy balance can use the measurements of solar irradiation and inlet temperature [5, 6]. On a clear day, nonlinear effect can be handled with model-based feedforward controllers with additional feedback controllers to remove offsets [7]. Model-based predictive control (MPC) [8, 9] is suitable for fairly smoothly changing conditions. Linguistic equation (LE) control includes solutions also for cloudy conditions and varying load situations [10]. MPC has been used for tuning the control of large setpoint changes [11]. Genetic algorithms have also been used for multiobjective tuning [12]. The main challenge is to handle harmful situations efficiently to reach an unattended operation as a part of a smart grid.

This paper summarizes LE control solutions used in varying operating conditions in solar thermal power plants.

II. 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 [3].

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. The field consists of parabolic-trough collectors (Fig. 1). Control is done by means of varying the flow pumped through the pipes in the field (Fig. 2) 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 ^{o}C. The temperature increase in the field may rise up to 110 degrees.

At the beginning of the daily operation, the oil was earlier 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. [13] In the latest tests, the inlet temperatures were high already in the start-up, since the oil flow was not first circulated in the field.

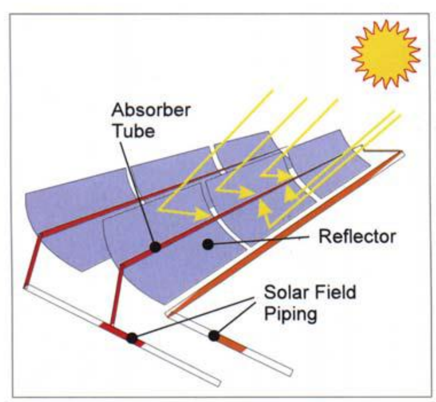

Figure 1. Parabolic-through collectors.

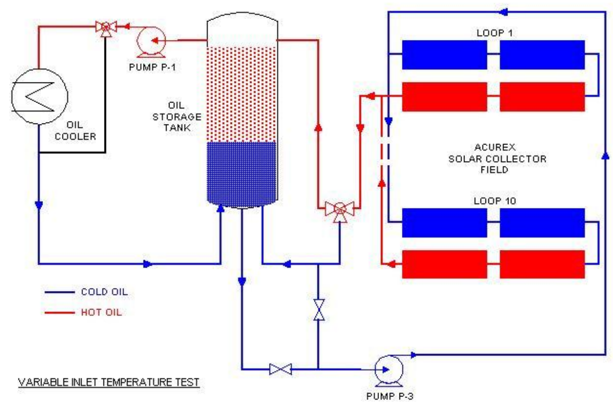

Figure 2. Solar collector field.

III. NONLINEAR SCALING

The scaling functions is a nonlinear mapping of variable values inside its range to a certain linguistic range [-2, 2]. The function is usually based on two second-order polynomials:

$$x_{lj} = f_{lj}(x_{lj}) = \begin{cases} a_{lj}^{-} X_{lj}^{2} + b_{lj}^{-} X_{lj} + c_{lj} & with \quad X_{lj} \in [-2, 0) \\ a_{lj}^{+} X_{lj}^{2} + b_{lj}^{+} X_{lj} + c_{lj} & with \quad X_{lj} \in [0, 2] \end{cases} \quad (1)$$

where a_{lj}^{-}, b_{lj}^{-}, a_{lj}^{+}, b_{lj}^{+} and c_{lj} are the coefficients of the polynomials for different features l of the variables j. Coefficient c_{lj} is the real value corresponding to the linguistic value 0. The membership definitions are monotonous and increasing [10]. These functions for the values of the variables (feature l=1) are analysed from the measurement data or defined from expertise: the coefficients are obtained from the real values corresponding to the linguistic values -2, -1, 0, 1 and 2. For dynamic models, the functions f_{2j} are defined for time delays (feature *l=2*). The LE controllers need additional membership definitions: error, change of error, original error and change of control (features *l=3, 4, 5* and *6*).

The linguistic value for the feature *l* of the input variable *j* is calculated according to equation

$$X_{lj} = \begin{cases} 2 & with \quad x_{lj} \geq \max(x_{lj}) \\ \dfrac{-b_{lj}^{+} + \sqrt{b_{lj}^{+2} - 4a_{lj}^{+}(c_{lj} - x_{lj})}}{2a_{lj}^{+}} & with \quad c_{lj} \leq x_{lj} \leq \max(x_{lj}) \\ \dfrac{-b_{lj}^{-} + \sqrt{b_{lj}^{-2} - 4a_{lj}^{-}(c_{lj} - x_{lj})}}{2a_{lj}^{-}} & with \quad \min(x_{lj}) \leq x_{lj} \leq c_{lj} \\ -2 & with \quad x_{lj} \leq \min(x_{lj}) \end{cases} \quad (2)$$

where $\max(x_{lj})$ and $\min(x_{lj})$ are maximum and minimum values of the real data corresponding to the linguistic values 2 and -2. After the linguistic level of the model output X_{lj} is calculated according to equation 1, it is converted to the real value of the output x_{lj} by using (1). The scaling functions can be recursively updated [14].

IV. INTELLIGENT CONTROL

All the equations used in LE controllers and intelligent analyzers are linear since the nonlinearities are handled with the nonlinear scaling.

A. Feedback Control

The multilevel control system consists of a nonlinear LE controller with predefined adaptation models, some smart features for avoiding difficult operating conditions and a cascade controller for obtaining smooth operation [4]. The basic controller is a PI-type LE controller represented by

$$f_{6i}^{-1}(\Delta u_{ij}) = K_P(i,j)\, f_{4j}^{-1}(\Delta e_j) + K_I(i,j)\, f_{3j}^{-1}(e_j) \quad (3)$$

Is nonlinear. The error e_j and the derivative of error Δe_j of the controlled variable *j* are mapped to the linguistic range by nonlinear scaling functions f_{lj}^{-1} where l is 3 and 4, respectively. The change of control Δu_{ij} is scaled back to the real scale with (2) where l is 6. The controller can be tuned by modifying the membership definitions and coefficients $K_P(i,j)$ and $K_I(i,j)$.

B. Intelligent Analyzers

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 working point

$$wp = f_{14}^{-1}(I_{eff}) - f_{15}^{-1}(T_{diff}), \quad (4)$$

which is obtained from the effective irradiation I_{eff} and the difference $T_{diff} = T_{out} - T_{in}$ between the outlet and the inlet temperatures, is the basis of the adaptation procedures.

The predictive braking indication is activated for very large errors. The calculated braking coefficient $bc_j(k)$ emphasizes the importance the derivative of the error:

$$K_P(i,j) = (1 + bc_j(k))\, K_P(i,j). \quad (5)$$

The asymmetry detection is based on the changes of the corrected irradiation. On a clear sunny day, the calculation can be based on the solar noon.

The fluctuation indicators, which were introduced to detecting cloudiness and oscillations, are the main improvements aimed for practical use. The indicator is obtained as a difference of two generalized norms whose orders are 30 and -30, respectively.

The intelligent indicators of the fast changes of the temperatures (inlet, outlet and difference) were compared with the intelligent trend analysis, which was introduced. The trend analysis is based on the scaled variables which are also used in the controller. New and revised actions required updates of the parameters.

C. 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 is not time enough to adapt online when there are strong disturbances.

The predictive braking and asymmetrical actions are activated in special situations (Fig. 3). 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.

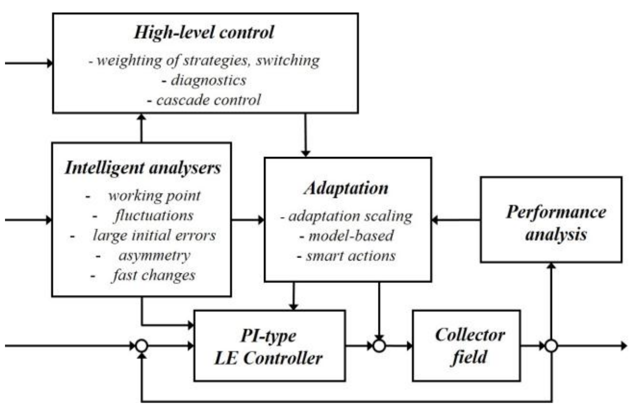

Figure 3. LE controller.

D. 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 [14]. The model-based extension is an essential part in moving towards reliable operation in cloudy conditions: the control system should operate without manual interventions. The high-level control moves towards control strategies to modify intelligent analyzers and adaptation procedures (Fig. 3).

V. RRESULTS

The control system facilitates an almost unattended operation. The nonlinear scaling already provides a wide operating range which is further extended by the adaptive control and finally, the model-based control introduces constraints for the operating area to avoid harmful situations.

A. Normal Operation

On clear days with high or fairly high irradiation, the feedforward controllers operate well. However, they are not used in the LE controllers since the control system needs to be ready for any disturbances. The setpoint tracking is fast with minimal oscillation throughout the nonlinear operating conditions although the oil properties change drastically with the temperature (Fig. 4). The working point adaptation handles efficiently and the temperature can be increased and decreased in spite of the irradiation changes.

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 at the active working point level. The oil flow changes smoothly: the fast changes are at the beginning of the step. Previously important working point corrections and limiting the fast changes are negligible. The predictive braking is activated for large step changes and the asymmetrical action is used only in the final stage of the step.

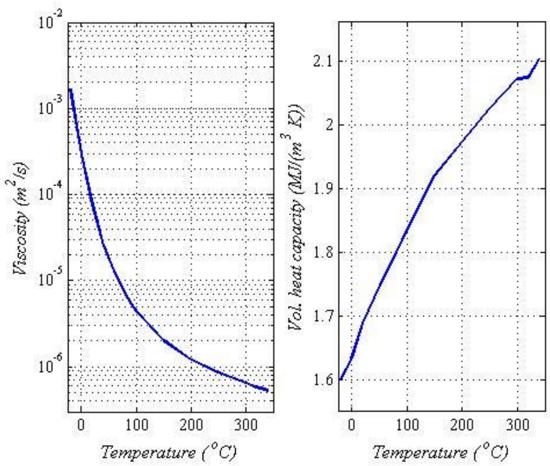

Figure 4. Oil properties.

B. 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(a)). The temporary setpoint correction allows the temperature to go down a few degrees. The modified setpoint is based on the working point *wp* which follows the mean value of the irradiation obtained by the fluctuation index (Fig. 5(b)). The temperature rises back during the 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 (Fig. 6(a)). After these periods, the field reached the normal operation in half an hour. For long heavy cloudy periods, the field can be kept in temperatures 160 - 210 ^{o}C for a long time if there are some sunny spells, e.g. two hours have been reached in tests. The working point corrections are very strong, but fast changes are not detected [15].

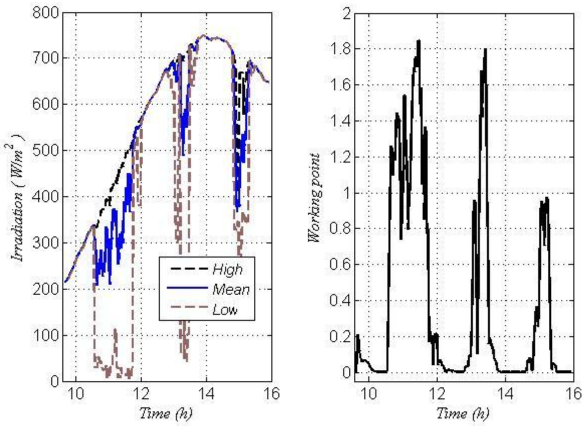

Figure 5. Irradiation disturbances on a cloudy day: (a) Irradiation, (b) Working point limit.

C. Load Disturbances

During a day, the temperature increases more or less smoothly in the storage tank (Figs. 6 and 7), but the use energy may cause fast disturbances. The controller should also handle these abrupt disturbances. An unintentional drop of 16.9 degrees in the inlet temperature is shown in Fig. 6(b). The disturbance lasted 20 minutes and the normal operation was retained in 50 minutes with only an overshoot of two degrees, but with some oscillations. The controller selected automatically appropriate actions. In another case, the setpoint was changed when the inlet temperature reached the minimum (Fig. 7). The working point limit was changed to allow a higher setpoint in the recovery. The temperature drop was smaller (7.5 degrees) but the overshoot slightly higher (2.5 degrees). Also the recovery took less time (30 minutes).

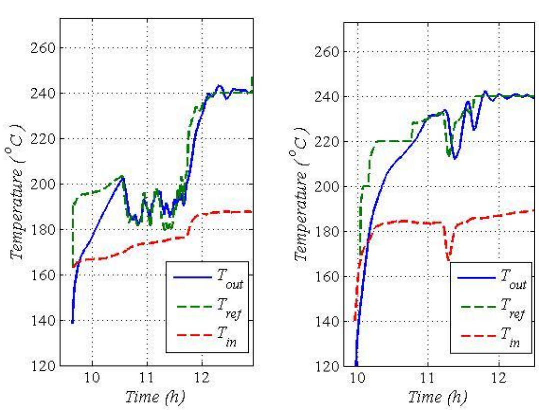

Figure 6. Disturbances during the start-up period: (a) clouds, (b) load.

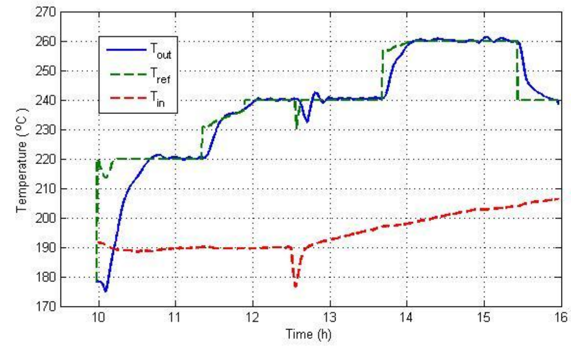

Figure 7. Disturbances during the start-up period.

D. Asymmetrical Corrections

The asymmetrical correction takes the irradiation changes into account. The setpoints are achieved in the range ±0.5 degrees with hardly any offset (Fig. 7). Around the solar noon, the setpoints are achieved very accurately even for high temperatures corresponding negative working points. The increase of the inlet temperature is smoothly compensated with the small changes of the oil flow and the setpoint is also accurately achieved after the load disturbances.

E. Optimisation

The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon (Fig. 8(a)). 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, 2-10 l/s. However, the power collection starts to decrease in too low flows. The maximum collected power is achieved when the oil flow is close to 6 l/s. A trade-off of the temperature and the flow is needed to achieve a good level for the collected power. Naturally, the power levels depend on the irradiation. The power surface is highly nonlinear because of the properties of the oil (Fig. 4).

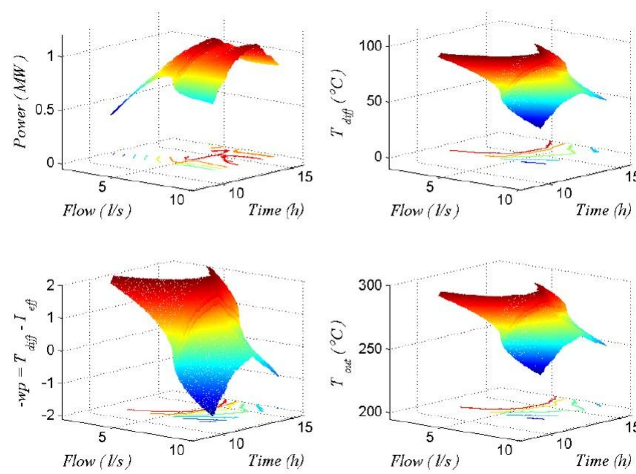

Figure 8. Operating area of a field: (a) power, (b) T_{diff}, (c) –wp, (d) T_{out}.

In the constrained optimization, the working point is chosen from the high power range and used in the model-based control to choose or limit the setpoint. Both the outlet temperature (Fig. 8(b)) and the temperature increase (Fig. 8(d)) are limited to keep the collector field in a good condition and avoid harmful situations. Limits are introduced in the following situations:

- During high irradiation periods, high outlet temperatures are avoided by keeping the working point high enough (Fig. 8(c)).
- In varying cloudy conditions, the working point limit is changed (Fig. 5(b)). In practice, the setpoint is kept on a low level to avoid a too high temperature increase during short sunny spells.
- Disturbances of the inlet temperatures introduce fluctuation to the outlet temperature. These fluctuations are taken into account in the same way as the irradiation disturbances.

In all these cases, the acceptable working point is limited by the oscillation risks and high viscosity of the oil during the start-up. The outlet temperatures and the collected energy will decrease but the operating area can be extended to more unfavorable conditions.

VI. Conclusions

The intelligent LE control system, which is based on intelligent analyzers 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. 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.

Acknowledgment

Experiments were carried out within the project "Intelligent control and optimisation of solar collection with linguistic equations (ICOSLE)" as a part of the project "Solar Facilities for the European Research Area (SFERA)" supported by the 7th Framework Programme of the EU (SFERA Grant Agreement 228296). Data analysis has been supported by the research program Measurement, Monitoring and Environmental Efficiency Assesment (MMEA) funded by the TEKES (the Finnish Funding Agency for Technology and Innovation).

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