Intelligent control and optimisation of a solar power plant in changing operating conditions

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ABSTRACT

Solar thermal power plants should collect thermal energy at the desired temperature range. A fast start-up and efficient operation in varying cloudy conditions without unnecessary shutdowns and start-ups are needed. The plant can be operated close to the design limits by using linguistic equation (LE) controllers as demonstrated 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. Solar energy can be collected only when the irradiation is high enough. The nights and the heavy cloud periods need to come up with the storage. The demand may also vary during the daytime. The LE control system is based on predefined model-based adaptation to activate special features when needed. The intelligent state indicators, which react well to the changing operating conditions, are 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.

1 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. 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 /1-7/. The control strategies include basic feedforward and PID schemes, adaptive control, model-based predictive control, frequency domain and robust optimal control and fuzzy logic control. Feedforward approaches based directly on the energy balance can use the measurements of solar irradiation and inlet temperature /8/. 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, even PID controllers operate for this purpose /9/. The classical internal model control (IMC) can operate efficiently in varying time delay conditions /10/. Genetic algorithms have also been used for multiobjective tuning /11/. For these solutions, the changing operating conditions and varying cloudy periods are the main difficulties.

Modelling and control activities with the linguistic equation (LE) methodology started by the first intelligent controllers implemented in 1996 /12,13/. The LE controllers use model-based adaptation and feedforward features, which are aimed for preventing overheating, and the controller presented in /14/ already took care of the actual setpoints of the temperature. The manual adjustment of the working point limit improved the operation considerably. Parameters of the LE controllers were first defined manually, and later tuned with neural networks and genetic algorithms. The LE based dynamic simulator is an essential tool in fine-tuning of these controllers /15/. Genetic algorithms have further reduced temperature differences between collector loops /16/. Manual actions are needed when the operating conditions are changing drastically. New data analysis methods based on generalised norms originate from condition monitoring applications /17/. A recursive scaling approach introduced in /18/ is the basis in detecting cloudy conditions and other oscillatory situations by analysing fluctuations of irradiation, temperature and oil flow /19/. The new indicators react well to the changing operating conditions and can be used in smart working point control to further reduce the need for manual actions.

This paper analyses the operation of new intelligent indicators introduced for adapting the LE controllers for start-up and operation in cloudy conditions and load disturbances. The analysis is based on recent experiments carried out in the *Acurex Solar Collectors Field of the Plataforma Solar de Almeria (PSA)* in Spain.

2 SOLAR POWER PLANT

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. 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. Control is achieved by means of varying the flow pumped through the pipes in the field (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 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, and the overall flow F to the collector field is controlled by the pump. /12/

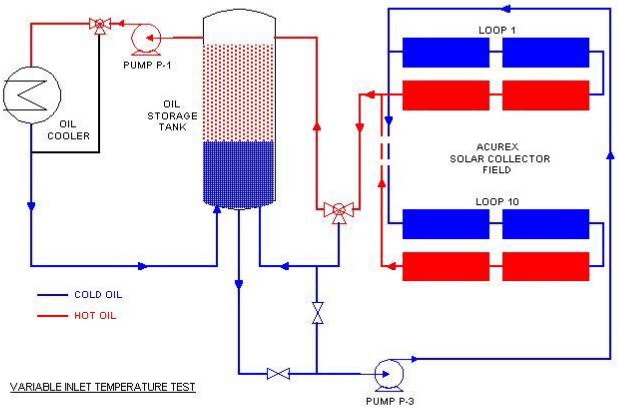

Figure 1 Layout of the Acurex solar collector field.

Energy collection depends on the oil flow, the temperature difference and the properties of the oil. High temperature differences are achieved by using low oil flow, and high flow leads to low temperature differences. In the start-up, the flow is limited by the high viscosity (Fig. 2(a)). The density decreases and the specific heat increases resulting a nonlinear increase of the volumetric heat capacity (Fig. 2 (b)). /13/ The highest energy collection in a time unit, i.e. the collected solar power, is achieved by selecting the optimal temperature difference, which depends on the irradiation and less on the ambient temperature. The optimisation is based on the oil properties and the inlet temperature, T_{in}. The effective irradiation is the direct irradiation modified by taking into account the solar time, declination and azimuth.

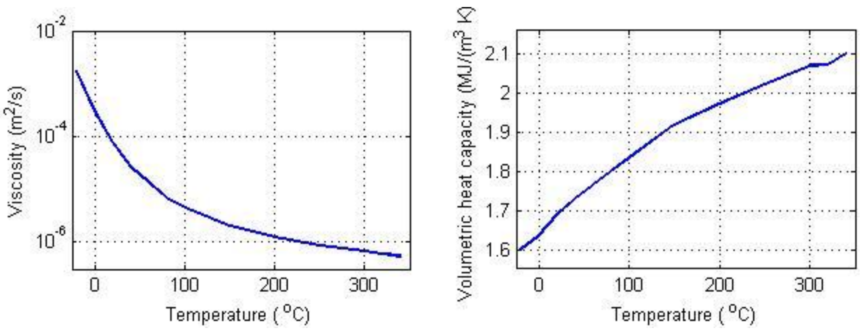

Figure 2 Oil properties (Santotherm 55): (a) viscosity, (b) volumetric heat capacity.

3 LINGUISTIC EQUATION CONTROL

The intelligent control system consists of a nonlinear linguistic equation (LE) controller with predefined adaptation models. For the solar collector field, the goal is to reach the nominal operating temperature 180 - 295 ^oC and keep it in changing operating conditions /18,19/. 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.

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. Several improvements were tested during the recent test campaign:

- The working point, which is obtained from the effective irradiation and the difference between the outlet and the inlet temperatures, is the basis of the adaptation procedures.

- The predictive braking indication is activated when a very large error is detected. A new solution was introduced to detecting the large error.

- The asymmetry detection was changed drastically: the calculation is now based on the changes of the corrected irradiation. The previous calculation based on the solar noon does not take into account actual irradiation changes.

- The new fluctuation indicators, which were introduced to detecting cloudiness and oscillations, are the main improvements aimed for practical use.

- 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.

Adaptive LE control uses correction factors which are obtained from the working point value. The predictive braking and asymmetrical actions are activated when needed. Intelligent indicators introduce additional changes of control if needed. The test campaign clarified the events, which activate the special actions. Each action has a clear task in the overall control system.

Model-based control was earlier used for limiting the acceptable range of the temperature setpoint by setting a lower limit of the working point. The new 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. This operated well in start-up and cloudy conditions. Oscillations are reduced efficiently in cloudy conditions and in the case of load disturbances. In heavy cloudy conditions, the controller keeps the field ready to start full operation. Even a short sunny spell raised the temperatures to the operating range.

Optimisation means adjusting the working point to choose a power range, which is suitable for the irradiation level and the energy demand, and takes into account the constraints of temperatures and viscosity of the oil. The temperatures increase with decreasing oil flow. The working point is chosen from the high power range and used in the model-based control to choose or limit the setpoint. The optimal temperature difference, $T_{diff}=T_{out}-T_{in}$, and the irradiation, is used in the model-based control to adjust the setpoint. Usually, the inlet temperature is slightly increasing during the day, which brings a possibility to use even higher outlet temperatures.

4 RESULTS

The new features of the controller were tested on a solar collector field at PSA in July 2012. On a clear day with high irradiation, the setpoint tracking was very fast: step changes from 15-25 degrees were achieved in 20-30 minutes with minimal oscillation. The working point adaptation was operating efficiently. The temperature was increased and decreased in spite of the irradiation changes. The working point limit activated the setpoint correction when the temperature difference exceeded the limit corresponding to the irradiation level. The oil flow changed smoothly: the fast changes were at the beginning of the step. On a fairly clear day with a lower and slightly varying irradiation, the setpoint correction was activated more often throughout the day (Fig. 3 (a)). The temperature followed the setpoint well with smaller offsets. Working point corrections and limiting the fast change were negligible.

Three cloudy periods are seen in Figure 3(b): 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. In the first case, 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. 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.

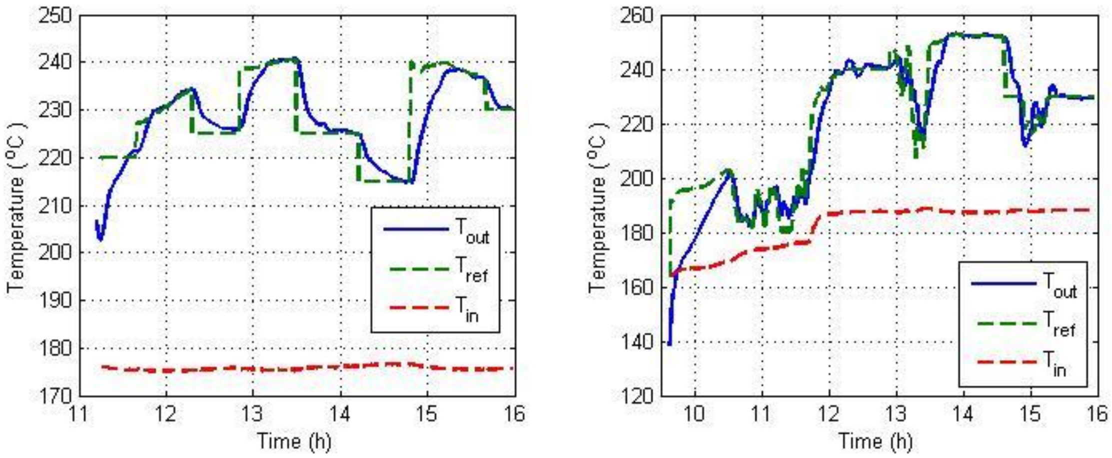

Figure 3 Test results of the LE controller: (a) a fairly clear day, (b) a cloudy day.

The controller reacts well to abrupt changes: the start of the fourth day 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 operation already started from low inlet temperature with the minimum flow. The whole start-up was very smooth despite the increasing irradiation and inlet temperature. The offset was removed with the new asymmetrical correction. Also the small temperature increase, which was caused when a new loop was taken into use, was efficiently corrected. The working point corrections were activated only in the beginning, and limiting the fast change was negligible throughout this period. The heavy clouds meant going back to the minimum flow, but also lower setpoints. The field was ready for normal operation and short sunny spells raised the temperature, but also the oil flow. The controller was ready to prevent a high overshoot, if the sky clears up. The field was in temperatures 160 - 210 ^{o}C 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.

On the fifth day, the start-up followed the setpoint defined by the working point limit (Fig. 4(a)). 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. The setpoint correction was too early and too large. The disturbance was repeated on the sixth day (Fig. 4(b)): maximum 13.5 degrees and 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 temperature drop was smaller (7.5 degrees) but the overshoot slightly higher (2.5 degrees). Also the recovery took less time (30 minutes). A third test was planned, but it was not possible to realize during the test period.

The new asymmetrical correction was activated in several periods on the sixth day (Fig. 4(b)). 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 ±0.5 degrees with hardly any offset. The change is considerable to the first days, when the outlet temperature 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.

The results are used in developing *optimisation* solutions for the energy collection. The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon (Fig. 5(a)). A trade-off of the temperature and the flow is needed to achieve a good level for the collected power (Fig. 5(b)). The power surface (Fig. 5(b)) is highly nonlinear because of the nonlinear properties of the oil (Fig. 2). Disturbances of the inlet temperatures introduce similar fluctuation to the outlet temperature. The acceptable range of the working point is limited: oscillation risks and high viscosity of the oil during the start-up must be taken into account. 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. High irradiation periods would lead to too high outlet temperatures, if the oil flow is too low, but this is avoided by keeping the working point under two. The maximum collected power is achieved when the oil flow is close to 6 l/s. Another maximum area close to the upper limit of the oil flow is achieved around the solar noon on a clear day.

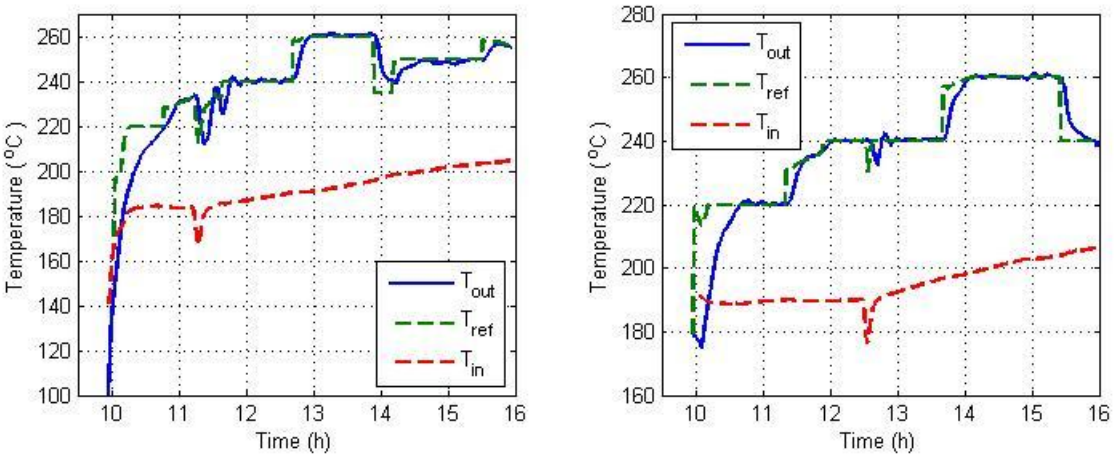

Figure 4 Test results of the LE controller on a fairly clear day including a load disturbance: (a) without special actions, (b) delayed actions. Improved asymmetrical action is used in (b).

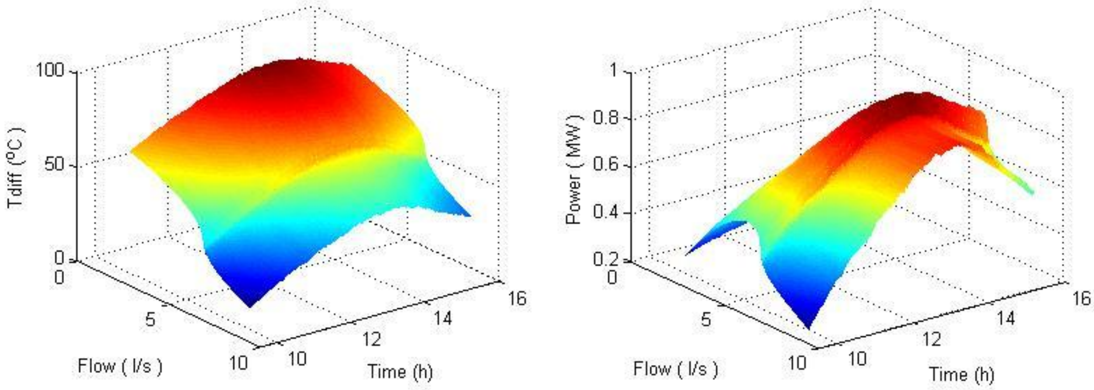

Figure 5 Energy collection alternatives vs. oil flow and time: (a) temperature difference across the field, (b) collected power.

5 CONCLUSIONS

The intelligent LE control system is based on predefined model-based adaptation technique, which activates special features when needed. Fast start-up, smooth operation and efficient energy collection is achieved even in variable operating condition. The new state indicators react well to the changing operating conditions and can be used in smart working point control to further improve the operation by reducing the need for manual actions. 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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