Optimisation of energy collection in a solar power plant

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Abstract: 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. Solar thermal power plants should 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. This study is based on tests done in Spain: the Acurex field supplies thermal energy 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 during the operation. Solar power plants can collect energy 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 operation mode should be adapted to current operating conditions, weather forecasts and plans of the energy use. Different scenarios are compared with an intelligent dynamic simulator based on case specific linguistic equation models.

Keywords: Solar energy, intelligent control, nonlinear systems, adaptation, optimisation, linguistic equations, modelling, simulation

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 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 (Camacho et al., 1997; Juuso, 1999; Johansen and Storaa, 2002; Cirre et al., 2007; Limon et al., 2008; Roca et al., 2011; Ayala et al., 2011). 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 (Camacho et al., 1992). 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 (Camacho et al., 1997). A feedforward controller has been combined with different feedback controllers, even PID controllers operate for this purpose (Valenzuela and Balsa, 1998). The classical internal model control (IMC) can operate efficiently in varying time delay conditions (Farkas and Vajk, 2002). Genetic algorithms have also been used for multiobjective tuning (Bonilla et al., 2012).

Linguistic equations (LE) have been used in various industrial applications (Juuso, 1999, 2004). Modelling and control activities with the LE methodology started by the first controllers implemented in 1996 (Juuso et al., 1997) and the first dynamic models developed in 1999 (Juuso et al., 2000). The LE based dynamic simulator is an essential tool in fine–tuning of these controllers (Juuso, 2005). The LE controllers use model-based adaptation and feedforward features, which are aimed for preventing overheating, and the controller presented in (Juuso and Valenzuela, 2003) 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 (Juuso, 2006). Data analysis methods are based on generalised norms, which have been developed for condition monitor-
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 (Juuso et al., 1998).

The Acurex field supplies thermal energy (1 MW) 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 °C. 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 reached. 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 reached.

The energy balance of the collector field can be represented by expression (Valenzuela and Balsa, 1998):

\[ I_{\text{eff}} A_{\text{eff}} = (1 - \eta_p)F \rho c T_{\text{diff}}, \]

where \( I_{\text{eff}} \) is effective irradiation (\( Wm^{-2} \)), \( A_{\text{eff}} \) effective collector area (\( m^2 \)), \( \eta_p \) a general loss factor, \( F \) flow rate of the oil (\( m^3s^{-1} \)), \( \rho \) oil density \( kgm^{-3} \), \( c \) specific heat of oil (\( Jkg^{-1}K^{-1} \)) and \( T_{\text{diff}} \) temperature difference between the inlet and the outlet (°C). The effective irradiation is the direct irradiation modified by taking into account the solar time, declination and azimuth.

3. MODELLING

The nonlinearities of the process is handled by nonlinear scaling of the variables. The parameters of the scaling functions are obtained by data analysis based on generalised norms and moments.

3.1 Scaling functions

The generalised norm is defined by

\[ ||M_j||_p = (M_j^p)^{1/p} = \left[ \frac{1}{N} \sum_{i=1}^{N} (x_{ij})^p \right]^{1/p}, \]

where the order of the moment \( p \in R \) is non-zero, and \( N \) is the number of data values obtained in each sample time \( \tau \). The norm (2) calculated for variables \( x_j \), \( j = 1, \ldots, n \), have the same dimensions as the corresponding variables. The norm \( ||M_j||_p \) can be used as a central tendency value if all values \( x_j > 0 \), i.e. \( ||M_j||_p \in R \). This norm combines two trends: a strong increase caused by the power \( p \) and a decrease with the power \( 1/p \). (Lahdelma and Juuso, 2008, 2011).

The mean, the harmonic mean and the root mean square (rms) are special cases of (2), which represents the norms between the minimum and the maximum corresponding the orders \( p = -\infty \) and \( p = \infty \), respectively. The norm values increase with increasing order. When \( p < 0 \), all the signal values should be non-zero, i.e. \( x \neq 0 \). When the order \( p \rightarrow 0 \), we obtain from (2) the geometric mean. The computation of the generalised norms can be divided into the computation of equal sized sub-blocks, i.e. the norm for several samples can be obtained as the norm for the norms of individual samples. (Lahdelma and Juuso, 2008, 2011) The norm can be extended to variables including negative values (Juuso, 2011).

Scaling functions, also known as membership definitions, provide nonlinear mappings from the operation area of the (sub)system to the linguistic values represented inside a real-valued interval \([-2, 2]\), denoted as the linguistic range, see (Juuso, 2004). The membership definitions consist of two second order polynomials: one for negative values, \( X \in [-2, 0) \), and one for non-negative values, \( X \in [0, 2] \). The polynomials are configured with five parameters defined by (2) and the generalised skewness,

\[ \gamma_{\text{skew}} = \frac{1}{N\sigma_j^2} \sum_{i=1}^{N} [(x_{ij})_1 - ||M_j||_p]^k. \]

The standard deviation \( \sigma_j \) is the norm (2) with the order \( p = 2 \). The parameters of the scaling functions can be recursively updated with by including new samples in calculations. The number of samples \( K \) can be increasing or fixed with some forgetting or weighting (Juuso, 2011).
3.2 Working point model

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. This nonlinear effect is handled with the working point LE model

\[ wp = a_1 \tilde{I}_{eff} + a_2 \tilde{T}_{diff} + a_3 \tilde{T}_{amb} + a_4, \]

where \( \tilde{I}_{eff} \), \( \tilde{T}_{diff} \) and \( \tilde{T}_{amb} \), which are obtained by nonlinear scaling of variables: efficient irradiation \( I_{eff} \), temperature difference between the inlet and outlet, \( T_{diff} = T_{out} - T_{in} \), and ambient temperature \( T_{amb} \), correspondingly. The outlet temperature \( T_{out} \) is the maximum outlet temperature of the loops. The ambient temperature is usually not used. Interactions are defined by constant coefficients \( a_1, a_2, a_3 \) and \( a_4 \). Working point, \( wp \), represents a fluctuation from the normal operation.

The working point variables already define the overall normal behaviour of the solar collector field, e.g. oscillatory behaviour is a problem when the temperature difference is higher than the normal. In the normal working point, \( wp = 0 \) the irradiation \( I_{eff} \) 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 \( I_{eff} \). Correspondingly, a low working point \( (wp < 0) \) means high \( \tilde{T}_{diff} \) compared to the irradiation level \( I_{eff} \). The normal limit \( (wp_{min} = 0) \) reduces oscillations by using slightly lower setpoints during heavy cloudy periods. This is not sufficient when the irradiation is high between cloudy periods. Higher limits \( (wp_{min} = 1) \) shorten the oscillation periods after clouds more efficiently.

3.3 Dynamic LE model

Conventional mechanistic models do not work, since there are problems with oscillations and irradiation disturbances. In dynamic LE models, the new temperature difference \( \tilde{T}_{diff}(t + \Delta t) \) between the inlet and outlet depends on the irradiation, oil flow and previous temperature difference:

\[ \tilde{T}_{diff}(t + \Delta t) = a_1 \tilde{T}_{diff}(t) + a_2 \tilde{I}_{eff}(t) + a_3 \tilde{F}(t) + a_4, \]

where coefficients \( a_1, a_2, a_3 \) and \( a_4 \) depend on operating conditions, i.e. each submodel has different coefficients. The membership definition of the outlet temperature does not depend on time; the bias term \( a_1 = 0 \). Model coefficients and the scaling functions for \( T_{diff}, I_{eff} \) and \( F \) are all model specific.

The fuzzy LE system with four operating areas is clearly the best overall model (Juuso, 2003, 2009): the simulator moves smoothly from start-up mode via low mode to normal mode and later visits shortly in high mode and low mode before returning to low mode in the afternoon. Even oscillatory conditions, including irradiation disturbances, are handled correctly. The dynamic LE simulator predicts well the average behaviour but requires improvements for predicting the maximum temperature since the process changes considerably during the first hour. For handling special situations, additional fuzzy models have been developed on the basis of the Fuzzy–ROSA method (Juuso et al., 2000).

4. INTELLIGENT LE 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 °C and keep it in changing operating conditions (Juuso, 2011, 2012). 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.

4.1 Intelligent analysers

Intelligent analysers are used for detecting changes in operating conditions to adapt activation and model-based control and to provide indirect measurements for the high-level control. Several improvements were tested during a 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.

4.2 Advanced control

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.

Intelligent trend analysis was performed for temperatures, irradiation and oil flow. These studies will be continued. The controller contains several parametric scaling functions for variables, errors, changes and corrections. The parameters were tuned before the test campaign by using previous test results. The parameters of the controller were updated for the revised actions. Offline tuning with the recursive approach will be done after the test campaign.

4.3 Optimisation

Energy collection depends on the oil flow, the temperature difference and the properties of the oil, see (1). High temperature differences are achieved by using low oil flow, and high flow leads to low temperature differences. The density decreases and the specific heat increases resulting a nonlinear increase of the term $\rho c$ (Fig. 2). In the start-up, the flow is limited by the high viscosity. (Juuso et al., 1998)

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, $T_{in}$. Then the working point (4), which is defined by the optimal $T_{diff}$ and the irradiation, is used in the model-based control to adjust the setpoint.

Fig. 2. Oil properties (Santotherm 55).

5. RESULTS

The new features of the controller was tested on a solar collector field at PSA in July 2012. The results are used in developing optimisation solutions for the energy collection.

5.1 Normal operation

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. Also the braking action was activated in these situations. Working point corrections and limiting the fast change were negligible.

On a fairly clear day with a lower and slightly varying irradiation, the setpoint correction was activated more often throughout the day. The temperature followed the setpoint well with smaller offsets. Working point corrections and limiting the fast change were negligible.

Fig. 3. Test results of the LE controller on a clear day.

5.2 Cloudy conditions

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. 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.

Fig. 5. Test results of the LE controller on a cloudy day.

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 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 when the new asymmetry correction of the controller. 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 °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.

Fig. 6. Test results of the LE controller on a clear morning followed by heavy clouds.

5.3 Load 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. The setpoint correction was too early and too large. The disturbance was repeated on the sixth day: 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.

Fig. 7. Test results of the LE controller on a fairly clear day including a load disturbance.

5.4 Asymmetry correction

The new asymmetry 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 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.

Fig. 8. Test results of the LE controller on a fairly clear day: asymmetry action.
5.5 Optimisation

The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon (Fig. 9). In this case, the inlet temperature is slightly increasing during the day (Fig. 7), which brought a possibility to use even higher outlet temperatures (Fig. 10). The temperatures increase with decreasing oil flow. A trade-off of the temperature and the flow is needed to achieve a good level for the collected power (Fig. 11). The working point (Fig. 12) is chosen from the high power range and used in the model-based control to choose or limit the setpoint.

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.

Fig. 9. Calculated temperature difference vs. oil flow on a fairly clear day.

Fig. 10. Calculated outlet temperature vs. oil flow on a fairly clear day.

Fig. 11. Power vs. oil flow on a fairly clear day.

Fig. 12. Working point vs. oil flow on a fairly clear day.

6. CONCLUSION

The intelligent LE control system is based on predefined model-based adaptation techniques. The system 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. 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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