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Intelligent Working Point Control for Solar Thermal Energy Collectors

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Abstract: Solar power plants are aimed to collect available thermal energy in a usable form at the desired temperature range. The thermal energy in form of hot oil can be used for electricity generation or a desalination plant. The Control is achieved by means of varying the flow pumped through the pipes in the field during the operation. In the utilization of the solar thermal energy, storages are highly important in integrating the collector systems with overall energy sources and usage: nights and the heavy cloud periods as well as load disturbances and changes need to come up with them. At a parabolic trough collector field, the linguistic equation (LE) controllers have shown reliable operation in varying operating conditions and extend the operation to varying cloudy and even heavy cloudy conditions and handle efficiently disturbances in energy demand. In a recent idea, the working point controller sets a goal for the operation by selecting the operating area which is then checked by the intelligent analysers to define the achievable setpoint. This improves the operation in connection with the other energy sources and the efficiency of the energy collection in varying operating conditions. Weather forecasts are needed in further scheduling the strengths of the collecting periods.

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

1. INTRODUCTION

Solar power plants are designed for collecting any available thermal energy in a usable form at the desired temperature range in spite of seasonal and daily cyclic variations as well as varying atmospheric conditions such as cloud cover, humidity, and air transparency. A fast start-up and efficient operation in varying cloudy conditions is important recovering the operation. A solar collector field is a good test platform for control methodologies (Camacho et al., 1997, 2012). The control strategies include basic feedforward and PID schemes extended with adaptive control, model-based predictive control, frequency domain and robust optimal control and fuzzy logic control.

Model-based approaches extend the operating area considerably. Feedforward approaches can be based directly on the energy balance and measurements of solar irradiation and inlet temperature. Lumped parameter models take 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. A feedforward controller can be combined with different feedback controllers or by the classical internal model control and tuned with genetic algorithms. Different approaches are discussed in (Juuso and Yebra, 2013a,b).

Linguistic equation (LE) controllers are compact solutions which use model-based adaptation and feedforward features, which are aimed for preventing overheating, and the controller presented by Juuso and Valenzuela (2003) 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 detection of the operating conditions is required in practical applications. Juuso (2012) introduced new state indicators for detecting cloudy conditions and other oscillatory situations by analysing fluctuations of irradiation, temperature and oil flow. Developments include advanced model-based LE control are discussed in (Juuso and Yebra, 2013a) and intelligent analysers (Juuso and Yebra, 2013b). The working point is highly important in varying operating (Juuso, 2017).

This paper focuses on the use of the smart working point controller in changing operating conditions. The analysis is based on the earlier campaigns at the *Acurex Solar Collectors Field of the Plataforma Solar de Almeria (PSA)* in Spain. The field has been closed.

2. SOLAR COLLECTOR FIELD

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 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 volumetric heat capacity increases very fast in the start-up stage and remains almost constant in the normal operating temperatures. The temperature increase in the field may rise up to 110 degrees. The overall flow F to the collector field is controlled by the pump. The plant can be operated close to the design limits which improves the productivity.

For the solar collector field, the traditional goal has been to reach the nominal operating temperature $180 - 295\ ^oC$ and keep it in changing operating conditions (Juuso, 2011, 2012; Juuso and Yebra, 2014). The test campaigns focused on achieving a smooth operation in changing operating conditions to operate in varying conditions to avoid unnecessary shutdowns and start-ups which cause unnecessary stress on the process equipment (Juuso and Yebra, 2014).

The new working point control is planned to be later tested at a new collector field since the Acurex field has been closed.

3. SMART ADAPTIVE CONTROL

The test campaigns were run with a smart adaptive controller based on a nonlinear controller enhanced with intelligent analysers to detect changes and fluctuations in operating conditions and an adaptation mechanisms to improve operation in varying situations. The working point turned out to be an highly important indicator for the existing flexibility of the operating range. Uncertainties of the operating area were analysed with a fluctuation indicator.

Feedback PI controllers use errors $e_j(k)$ and derivatives of the errors $\Delta e_j(k)$ calculated for the controlled variables j at each time step k. The error variable is the deviation of the outlet temperature from the set point. In PI-type LE controllers extend these controllers to nonlinear operation by mapping the real values to the linguistic range $[-2, 2]$ 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 scaled 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.

In the solar collector field, the PI-type LE controller has 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. For the normal operating conditions, this control can run the collector field throughout the day.

The *Working point*

$$wp = \tilde{I}_{eff} - \tilde{T}_{diff}, \tag{1}$$

is an indicator for using the level of efficient irradiation, $\tilde{I}_{eff}$, in increasing the temperature in the field, $\tilde{T}_{diff}$. The levels 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. 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 that $\tilde{T}_{diff}$ is low compared with the irradiation level $\tilde{I}_{eff}$. Correspondingly, a low working point ($wp < 0$) means that $\tilde{T}_{diff}$ is high 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.

The *fluctuation indicators* were introduced to detecting cloudiness and oscillations (Juuso, 2012). The cloudy conditions are detected by calculating the difference of the high and the low values of the corrected irradiation is used as an indicator of fluctuations, which is based on the scaled values of high positive and negative orders.

Model-based control defines the acceptable range of the temperature setpoint by setting a lower limit of the working point. The working point (1), is used to calculate the setpoint for T_{out} from T_{in} and I_{eff} after selecting an appropriate working point wp. The fluctuation indicators are used for modifying the lower working point limit to react better to cloudiness and other disturbances. This sets the maximum for the temperature difference T_{diff} and lowers the setpoint of T_{out} if the operation conditions require that. The working point control is the key to the automatic high level control.

The new role of the model-based control is in adapting the operation to the changing requirements of the overall energy system. During the test campaigns, the setpoint was originally chosen manually and the working point and fluctuations were used to introduce additional limitations for it to reduce oscillations and possibly harmful situations.

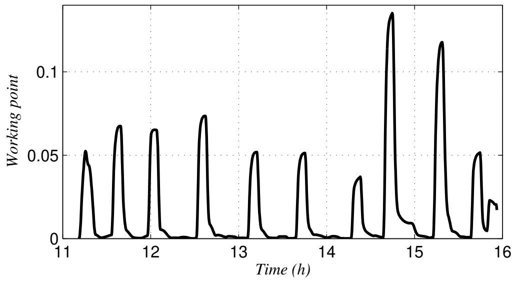
4. WORKING POINT CONTROL

Adaptive and model-based control meant that the collector field could be controlled by manipulating the working point. In cloudy conditions, it was necessary to take the fluctuations into account as well. The working point (1) enhanced with the fluctuation effects provides very useful information about the status of the field. This has not yet tested in full operation, but the previous tests at PSA demonstrate the operability of these ideas in varying situations. The normal nonlinear operation is sufficient during clear days but the adaptation is needed in cloudy conditions and when fast load disturbances are introduced. This paper focuses on the effects of the working point. The detailed test results on temperatures and oil flow have been presented in Juuso and Yebra (2013a,b). This section discusses the model-based applications of these solutions in integrating with overall energy systems.

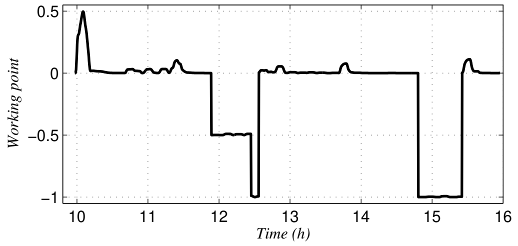
4.1 Normal operation

On clear days with high or fairly high irradiation, drastic working point changes are not needed (Fig. 1(a)) and the setpoint tracking is acceptable without strong special actions: step changes from 15-25 degrees are achieved in

20-30 minutes with minimal oscillation when the irradiation is changing smoothly. The working point adaptation operates efficiently and the temperature can be increased and decreased in spite of the irradiation changes. In this case, the changes of the working point are minimal and are introduced in connection with setpoint changes. The predictive braking and asymmetrical actions can be used on clear days.



(a) Working point on a smooth clear day.



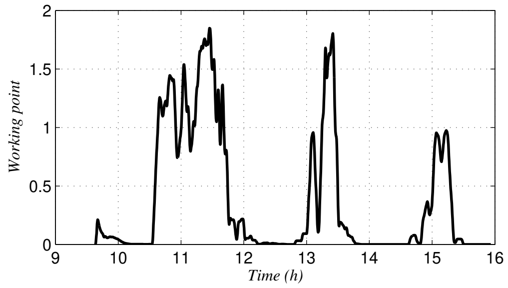
(b) Variations of the working points.

Fig. 1. Working point of the LE controller on a clear day: (a) normal operation with minimal working point changes, (b) working point is used in compensating disturbances (Juuso and Yebra, 2013b).

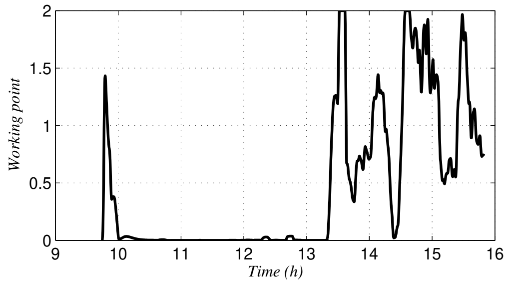
Originally, the working point was always positive and high values were used if there were disturbances caused by varying cloudiness. However, also the negative values of the working point can be used (Fig. 1(b)), e.g. in disturbance rejection. These results are promising for using the working point for adapting the operation with higher level requirements.

4.2 Cloudy conditions

The working point becomes highly important on cloudy days. Three cloudy periods were handled efficiently with the working point changes, which were automatically introduced in these situations (Fig. 2(a)). 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 controller used high oil flow levels when the sky was clearing up. The same approach operated well for the other two cloudy 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) Cloudy periods.



(b) A period of heavy clouds.

Fig. 2. Working point of the LE controller on cloudy days.

Heavy cloudy periods change the operating conditions in an abrupt way. The working point moves towards level two (Fig. 2(b)) and the outlet temperature is kept close to the inlet temperature by limiting strongly T_{diff}. The field is ready to start if the irradiation conditions improve. Already short sunny spells introduce changes in T_{out}.

The working point keeps the field in readiness for starting full operation.

4.3 Start-up and load disturbances

The model-based control of the start-up was tested on a smoothly operating clear start of the day. The very efficient start-up followed the setpoint defined by the working point limit In this case, the high working point values were also used the start-up phase (Fig. 2(b)).

A disturbance of T_{in} was introduced on a fairly clear day: the working point value was changed when the inlet temperature dropped a maximum of 13.5 degrees and 15 minutes. The setpoint was changed when the inlet temperature reached the minimum. The working point limit was changed (Fig. 1(b)) to allow a higher setpoint in the recovery. The temperature T_{out} dropped 7.5 degrees followed an overshoot of 2.5 degrees. The operation recovered in 30 minutes.

4.4 Optimisation

The operating area is limited by the working point wp (Fig. 3). The area close to $wp = 0$ is default on clear days. This is consistent with the idea that the normal operation does not need any working point changes. The operating area is much wider when the negative values of the working point are accepted. Higher temperatures and powers can be achieved but then also the hard limits of T_{out} and T_{diff} must be taken into account. The cloudy conditions reduce the negative range of the working point (Fig. 2), which means less possibilities to use high temperatures and power.

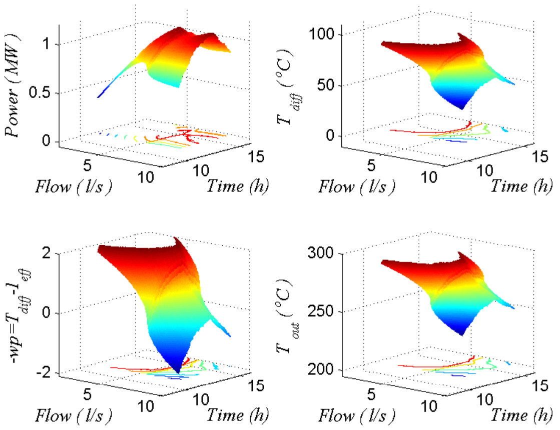


Fig. 3. Operating areas are chosen by the working point wp, example on a clear day.

5. DISCUSSION

In the tests, the working point was changing during the operation (Figs 1 and 2) to keep smooth operation when the operating conditions were changing. The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon. The working point provides a trade-off of the temperature and the flow is needed to achieve a good level for the collected power. The power surface is highly nonlinear because of the properties of the oil. Disturbances of the inlet temperatures introduce fluctuation to the outlet temperature. A good working point can reduce the oscillation risks and take into account the high viscosity of the oil during the start-up. During high irradiation periods, high outlet temperatures are avoided by keeping the working point high enough.

The working point (1) balances the correction factors of the control actions and takes into account the limits of the setpoint T_{ref}. Effects of the fluctuations are taken into use through the changes of wp and the predictive braking and asymmetry corrections are used only if the conditions are smooth enough.

The working point can be selected from wide range (Fig. 1(b)) and it reacts well to both cloudy periods (Fig. 2(a)) and long periods of heavy clouds (Fig. 2(b)). This is very promising for model-based adaptation and integration with other energy sources in real applications. The operating range can be extended much wider within the ranges shown in Fig. 3. The starting of the new collector field is delayed, the research will be continued with simulators before going to the testing with the new field.

The working point control described above is used to choose a preferred setpoint which has been earlier given manually. This setpoint is used only if the operating conditions allow it. The setpoint can be understood as a goal and the intelligent analysers reduce it need as it was explained for cloudy conditions.

6. CONCLUSION

The working point controller sets a goal which is further processed by the intelligent LE control system which is the essential part in the system consisting of intelligent analysers and predefined model-based adaptation techniques. The real-time working point is the key to adaptation and integration within the operating area: 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. The working point controller reduces oscillations during cloudy conditions and keeps the field ready in heavy cloudy conditions to start full operation if the irradiation gets smoother.

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