Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Smart adaptive control of a solar collector field

Esko K. Juuso * **Luis J. Yebra** **

* *Control Engineering Laboratory, Department of Process and Environmental Engineering, FI-90014 University of Oulu, Finland, (e-mail: esko.juuso@oulu.fi)*
** *CIEMAT, Plataforma Solar de Almería, Automatic Control Group Crta. de Senés s/n, 04200 Tabernas, Almería, Spain, (luis.yebra@psa.es)*

Abstract: Solar power plants collect available thermal energy in a usable form at the desired temperature range. Efficient operation requires a fast start-up and reliable operation in varying 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 nights and the heavy cloud periods need to come up with the storage. The smart LE controllers extend the operation to varying cloudy conditions and handle efficiently disturbances in energy demand. The predefined model-based adaptation techniques are combined with special features when needed. 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. The controller reacts efficiently on the setpoint changes, clouds and load disturbances. The predictive braking action allows fast changes in control actions. 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.

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; Camacho et al., 2012). 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 (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 equation (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. Data analysis methods are based on generalised norms (Juuso and Lahdelma, 2010) and extended to a recursive version of the scaling approach was introduced in Juuso (2011). New state indicators for detecting cloudy conditions and other oscillatory situations by analysing fluctuations of irradiation, temperature and oil flow (Juuso, 2012). Recent developments include advanced model-based LE control are discussed in (Juuso and Yebra, 2013a) and intelligent analysers (Juuso and Yebra, 2013b).

This paper presents the operation of the LE controller in changing operating conditions at the *Acurex Solar Col-*

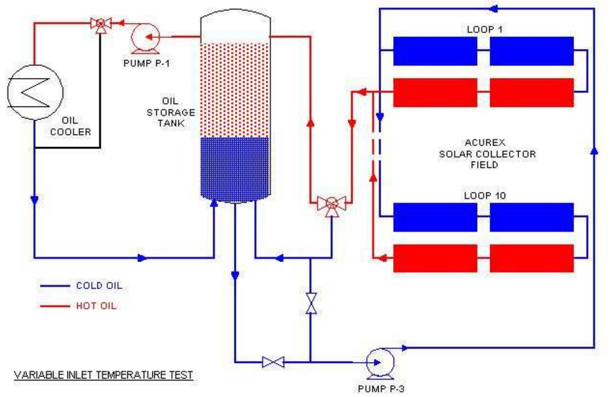


Fig. 1. Layout of the Acurex solar collector field.

lectors Field of the Plataforma Solar de Almeria (PSA) in Spain, the field is presented in Section 2. The control system including intelligent analysers and adaptation solutions is described in Section 3. Results are discussed in Section 4 and the paper is concluded in Section 5.

2. 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 (Juuso et al., 1998).

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: the overall flow F to the collector field is controlled by the pump. (Juuso et al., 1997)

The latest test campaign in July 2012 focused on achieving a smooth operation in changing operating conditions to avoid unnecessary stress on the process equipment.

3. SMART ADAPTIVE 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. For the solar collector field, the goal is to reach the nominal operating temperature $180 - 295\ ^oC$ and keep it in changing operating conditions (Juuso, 2011, 2012). The control system is based a PI-type LE controller enhanced with several Intelligent analysers and adaptive modules (Fig. 2). The high-level control provides a full weighting of these features.

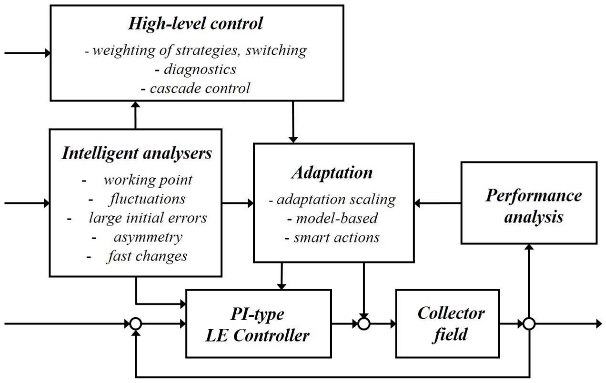


Fig. 2. Smart adaptive LE control system.

3.1 Feedback LE controller

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, these real values are mapped 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.

For each manipulating variable i, the controller is represented by

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

where the direction of the control action is fixed with the coefficients $K_P(i,j)$ and $K_I(i,j)$. The strengths of 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. 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 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.

3.2 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. Several samples with length τ are used at each control step.

The *Working point model*

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

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 and remains almost constant in the normal operating temperatures.

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.

The *predictive braking indication* is activated when a very large error is detected. 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:

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

A new solution has been 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 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.

The *new fluctuation indicators*, which were introduced to detecting cloudiness and oscillations, are the main 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:

$$\Delta x_j^F(k) = ||^{K_s\tau}M_j^{p_h}||_{p_h} - ||^{K_s\tau}M_j^{p_l}||_{p_l}, \qquad (6)$$

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. (Juuso, 2012)

The *intelligent indicators of the fast changes* of the temperatures (inlet, outlet and difference) based on intelligent indices which detect anomalies: fast change of the inlet temperature obtained by

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

too fast outlet temperature increase by the value range

$$\Delta T_{out}^R(k) = \max_{i=k-n_L,\ldots,k}\{T_{out}(i)\} - \min_{i=k-n_L,\ldots,k}\{T_{out}(i)\}, \qquad (8)$$

if T_{out} has increased during the period, and too high temperature difference by an overshoot

$$\Delta T_{out}^H(k) = \max\{0, T_{out}(k) - T_{out}^{sp}\}. \qquad (9)$$

The window for the recent values is defined by delay n_L.

3.3 Adaptive and model-based 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.

The additional intelligent features (7), (8) and (9), which detect anomalies, introduce an additional change of control:

$$\Delta u_j^{\widetilde{CH}}(k) = c_1\Delta\widetilde{T_{in}^H}(k) + c_2\widetilde{T_{out}^R}(k) + c_3\Delta\widetilde{T_{out}^H}(k), \qquad (10)$$

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 was earlier used for limiting the acceptable range of the temperature setpoint by setting a lower limit of the working point. The model is the working point model (4), which is used to calculate the setpoint for T_{out} from T_{in} and I_{eff} after selecting an appropriate working point *wp*. 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.

4. RESULTS

The new features of the controller were tested on a solar collector field at PSA in July 2012 to compare their operation with the previously implemented modules.

4.1 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 was operating efficiently and the temperature can be increased and decreased in spite of the irradiation changes. The oil flow changes smoothly: the fast changes are at the beginning of the step (Fig. 4). Also the braking action is activated in these situations. Working point corrections and limiting the fast changes are negligible. The predictive braking was activated, but the asymmetrical action was not yet available.

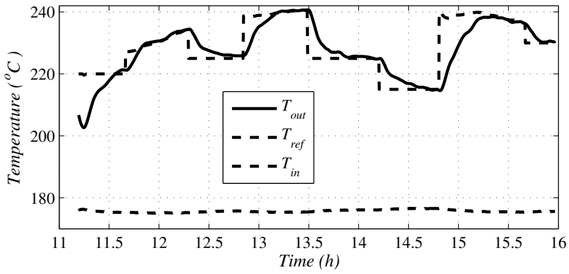


Fig. 3. Test results of the LE controller on a fairly clear day (Juuso and Yebra, 2013b).

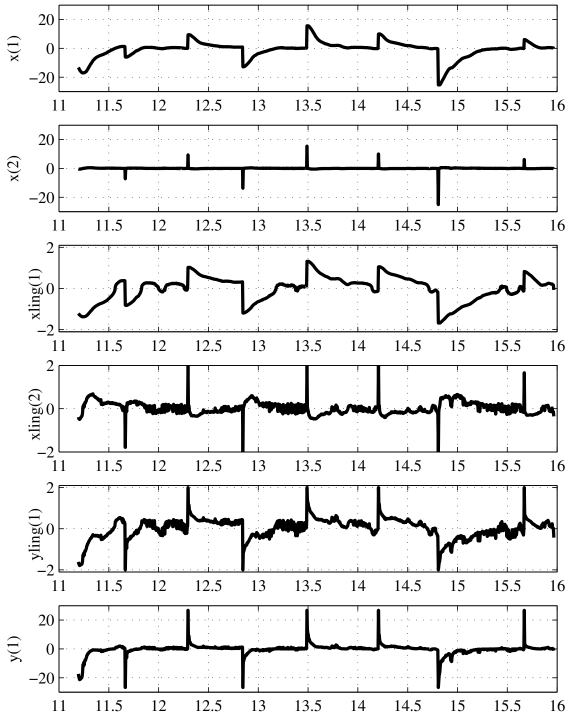
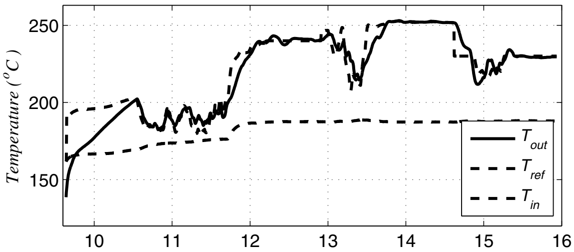
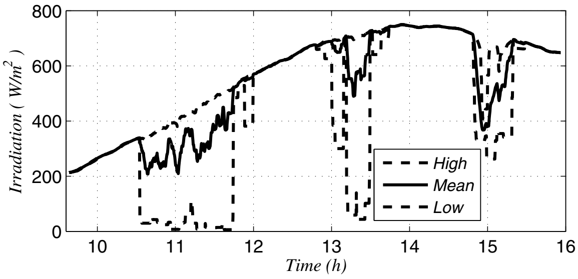


Fig. 4. Operation of the LE controller on a fairly clear day: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

4.2 Cloudy conditions



(a) Outlet temperature.



(b) Irradiation.

Fig. 5. Test results of the LE controller on a cloudy day (Juuso and Yebra, 2013b).

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)). In the first case (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. The controller used high oil flow levels when the sky was clearing up. Also the changes of control were reacting strongly. 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.

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 (Juuso and Yebra, 2013a).

4.3 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 disturbance was repeated on the sixth day (Fig. 7(a)): 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 change of

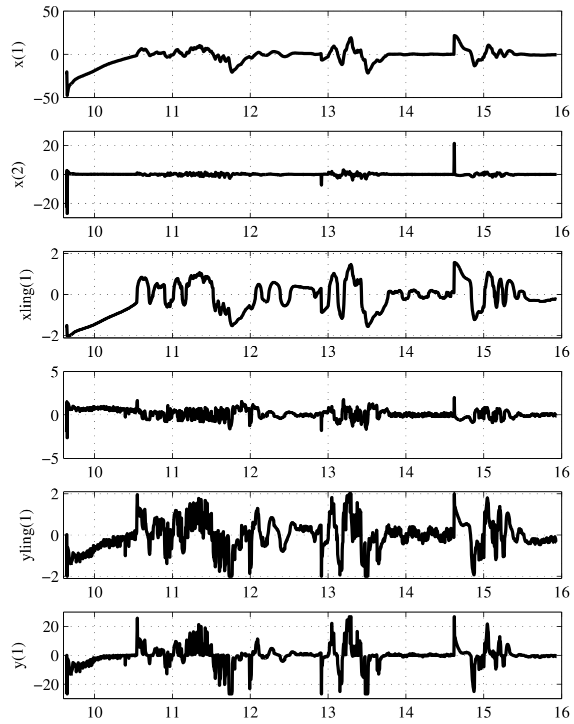
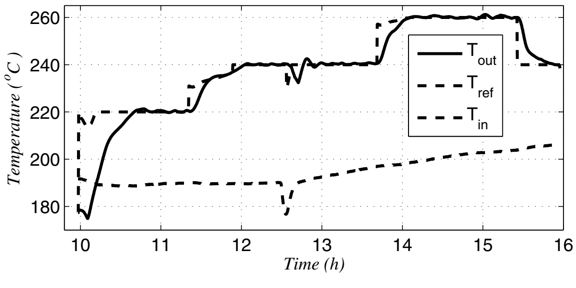
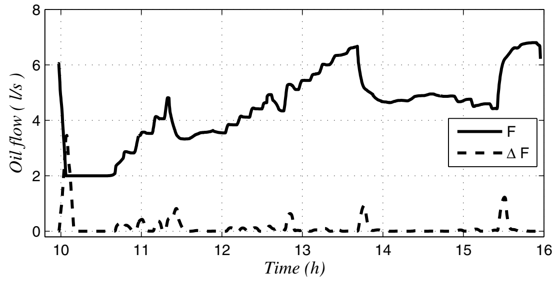


Fig. 6. Operation of the LE controller on a cloudy day: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

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).



(a) Outlet temperature.



(b) Oil flow.

Fig. 7. Test results of the LE controller on a clear day: asymmetral action (Juuso and Yebra, 2013b).

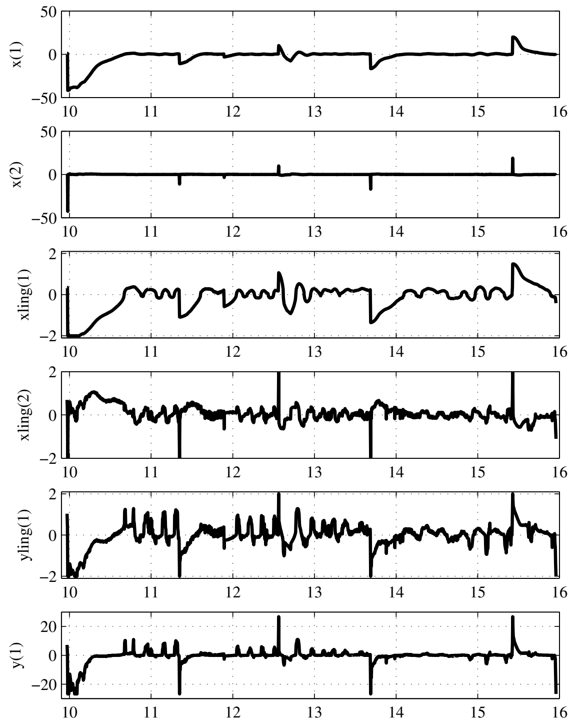


Fig. 8. Operation of the LE controller on a clear day, including asymmetry action: $x = [e, \Delta e]$, $xling = [\tilde{e}, \widetilde{\Delta e}]$, $yling = \widetilde{\Delta u}$ and $y = \Delta u$.

4.4 Asymmetrical correction

The new asymmetrical correction was activated in several periods on the sixth day. 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 (Fig. 7(a)). 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 even for high temperatures corresponding negative working points. The increasing inlet temperature is smoothly compensated with small oil flow changes and the setpoint is also accurately achieved after the load disturbance (Fig. 7(b)). The asymmetrical action increases the positive changes before the solar noon and the negative changes after that (Fig. 8).

4.5 Feasible operating area

The temperature increase in the collector field naturally depends on the irradiation, which is the highest close to the solar noon. 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 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. During high irradiation periods, high outlet temperatures are avoided by keeping the working point high enough.

5. CONCLUSION

The smart 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 changes 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.

ACKNOWLEDGEMENTS

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).

REFERENCES

Ayala, C.O., Roca, L., Guzman, J.L., Normey-Rico, J.E., Berenguel, M., and Yebra, L. (2011). Local model predictive controller in a solar desalination plant collector field. *Renewable Energy*, 36, 3001–3012. Doi: 10.1016/j.renene.2011.03.037.

Bonilla, J., , Yebra, L.J., Dormido, S., and Zarza, E. (2012). Parabolic-trough solar thermal power plant simulation scheme, multi-objective genetic algorithm calibration and validation. *Solar Energy*, 86, 531–540. Doi: 10.1016/j.solener.2011.10.025.

Camacho, E., Berenguel, M., and Rubio, F.R. (1997). *Adaptive Control of Solar Plants*. Springer, London.

Camacho, E.F., Berenguel, M., Rubio, F.R., and Martinez, D. (2012). *Control of Solar Energy Systems*. Advances in Industrial Control. Springer, London.

Camacho, E., Rubio, F., and Hughes, F. (1992). Self-tuning control of a solar power plant with a distributed collector field. *IEEE System Control Magazine*, 12(2), 72–78.

Cirre, C.M., Berenguel, M., Valenzuela, L., and Camacho, E. (2007). Feedback linearization control for a distributed solar collector field. *Control engineering Practice*, 15, 1533–1544. Doi: 10.1016/j.conengprac.2007.03.002.

Farkas, I. and Vajk, I. (2002). Internal model-based controller for a solar plant. In L. Basanez and J.A. de la Puente (eds.), *Proceedings of the 15th Triennial World Congress, Barcelona, Spain, July 21-26, 2011*, 49–54. IFAC. http://www.ifac-papersonline.net/.

Johansen, T.A. and Storaa, C. (2002). Energy-based control of a distributed solar collector field. *Automatica*, 38, 1191–1199.

Juuso, E. and Lahdelma, S. (2010). Intelligent scaling of features in fault diagnosis. In *Proceedings of the 7th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, 22-24 June, 2010, Stratford-upon-Avon, UK*, volume 2, 1358–1372. Curran Associates, NY, USA. ISBN 978-1-61839-013-4.

Juuso, E.K. (1999). Fuzzy control in process industry: The linguistic equation approach. In H.B. Verbruggen, H.J. Zimmermann, and R. Babuška (eds.), *Fuzzy Algorithms for Control, International Series in Intelligent Technologies*, volume 14 of *International Series in Intelligent Technologies*, 243–300. Kluwer, Boston. Doi: 10.1007/978-94-011-4405-6_10.

Juuso, E.K. (2011). Recursive tuning of intelligent controllers of solar collector fields in changing operating conditions. In *Proceedings of the 18th World Congress The International Federation of Automatic Control, Milano (Italy) August 28 - September 2, 2011*, 12282–12288. IFAC. Doi: 10.3182/20110828-6-IT-1002.03621.

Juuso, E.K. (2012). Model-based adaptation of intelligent controllers of solar collector fields. In *Proceedings of 7th Vienna Symposium on Mathematical Modelling, February 14-17, 2012, Vienna, Austria, Part 1*, volume 7, 979–984. IFAC. Doi: 10.3182/20120215-3-AT-3016.00173.

Juuso, E.K., Balsa, P., and Leiviskä, K. (1997). Linguistic Equation Controller Applied to a Solar Collectors Field. In *Proceedings of the European Control Conference - ECC'97, Brussels, July 1 - 4, 1997*, volume 5, TH-E I4, paper 267 (CD-ROM), 6 pp.

Juuso, E.K., Balsa, P., and Valenzuela, L. (1998). Multilevel linguistic equation controller applied to a 1 MW solar power plant. In *Proceedings of the ACC'98, Philadelphia, PA, June 24–26, 1998*, volume 6, 3891–3895. ACC.

Juuso, E.K. and Valenzuela, L. (2003). Adaptive intelligent control of a solar collector field. In *Proceedings of Eunite 2003 Symposium, July 10-11, 2003, Oulu, Finland*, 26–35. Wissenschaftsverlag Mainz, Aachen.

Juuso, E.K. and Yebra, L. (2013a). Model-based intelligent control of a solar energy collector field. In *Proceedings of 8h EUROSIM Congress on Modelling and Simulation, 10-13 September, 2013, Cardiff, UK*, 513–518. IEEE. Doi:10.1109/EUROSIM.2013.92.

Juuso, E.K. and Yebra, L. (2013b). Optimisation of solar energy collection with smart adaptive control. In *USB Proceedings of IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, 10-14 November, 2013, Vienna, Austria*, 7930–7935. IEEE. Doi: 10.1109/IECON.2013.6700459.

Limon, D., Alvarado, I., Alamo, T., Ruiz, M., and Camacho, E.F. (2008). Robust control of the distributed solar collector field ACUREX using MPC for tracking. In *Proceedings of 17th IFAC World Congress, Seoul, Korea, July 6-11, 2008*, volume 17, 958–963. IFAC. http://www.ifac-papersonline.net/.

Roca, L., Guzman, J.L., Normey-Rico, J.E., Berenguel, M., and Yebra, L. (2011). Filtered smith predictor with feedback linearization and constraints handling applied to a solar collector field. *Solar Energy*, 85, 1056–1067. Doi: 10.1016/j.solener.2011.02.026.

Valenzuela, L. and Balsa, P. (1998). Series and parallel feedforward control schemes to regulate the operation of a solar collector field. In *Proceedings of the 2nd User Workshop TMR Programme at Plataforma Solar de Almeria, November 10-11, 1998*, 19–24. Ciemat.