# MODELLING AND CONTROL OF A SOLAR THERMAL POWER PLANT

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Abstract: Model-based control design is essential in the control of solar power plants. Dynamic linguistic equation (LE) models operate accurately in most operating conditions. Smooth transitions between submodels are based on fuzzy logic and fuzzy set systems are also used for special situations. The hybrid simulator has been tested with extensive process data, and the adaptive controller tuned with these models reduces considerably temperature differences between collector loops. Efficient energy collection is achieved even in variable operating condition. Distributed parameter models extend the operability to drastic changes, e.g. start-up and large load disturbances, and local disturbances and malfunctioning.

Keywords: Solar power plant, dynamic modelling, intelligent simulation environments, non-linear models, linguistic equations, fuzzy set systems

## 1. INTRODUCTION

Solar power plants should collect any available thermal energy is in a usable form at the desired temperature range, which improves the overall system efficiency and reduces the demands placed on auxiliary equipments. In cloudy conditions, the collector field is maintained in a state of readiness for the resumption of full-scale operation when the intensity of the sunlight rises once again. Solar collector field is is good test platform for various control methodologies (Camacho *et al.*, 1997; Juuso, 1999).

Lumped parameter models taking into account the sun position, the field geometry, the mirror reflectivity, the solar radiation and the inlet oil temperature have been developed for a solar collector field (Camacho *et al.*, 1997). Feedforward controllers based lumped and distributed energy balances extended these models (Valenzuela and Balsa, 1998; Farkas and Vajk, 2002).

Linguistic equations have been used in various industrial applications (Juuso, 1999; Juuso, 2004*b*). The robust dynamic simulator based on linguistic equations is an essential tool in fine–tuning of these controllers (Juuso, 2003). This data-driven dynamic LE modelling approach is combined with a dynamic energy balance and extended to developing distributed parameter models (Juuso, 2004*a*).

This paper summarizes modelling and control activities with the LE methodology from the first LE controllers implemented in 1996 (Juuso *et al.*, 1997) and the first dynamic LE models developed in 1999 (Juuso *et al.*, 2000) to the multilevel LE controllers and the recent extensions to distributed parameter models. The paper also presents how the overall system is used in control design. All the experiments have been carried out in the *Acurex Solar Collectors Field of the Plataforma Solar de Almeria* located in the desert of Tabernas (Almeria), in the south of Spain.

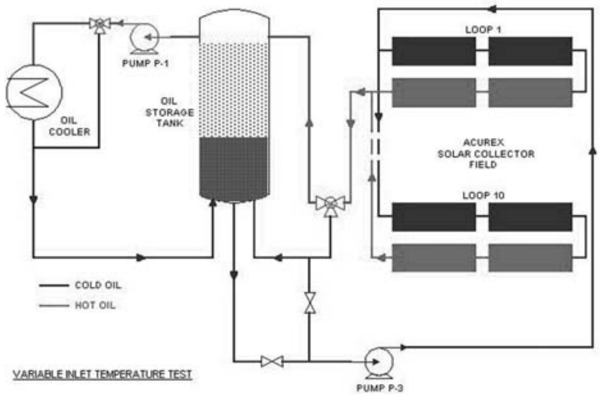

Fig. 1. Layout of the Acurex solar collector field.

## 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. In addition to seasonal and daily cyclic variations, the intensity depends also on atmospheric conditions such as cloud cover, humidity, and air transparency. Unnecessary shutdowns and start-ups of the collector field are both wasteful and time consuming. Finally if the control is fast and well damped, 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 solar field consists of parabolic–trough collectors (Juuso *et al.*, 1997). Control is achieved by means of varying the flow pumped through the pipes during the plant operation. In addition to this, the collector field status must be monitored to prevent potentially hazards situations, e.g. oil temperatures greater than 300 $^oC$. The temperature increase in the field may rise upto 110 degrees. In the beginning of the daily operation, the oil is circulated in the field, and the valve to storage system (Fig. 1) is open when an appropriate outlet temperature is achieved.

An overview of possible control strategies presented in (Camacho *et al.*, 1997) include basic feedforward and PID schemes, adaptive control, model-based predictive control, frequency domain and robust optimal control and fuzzy logic control. A comparison of different intelligent controllers is presented in (Juuso, 1999). A linguistic equation (LE) controller was first implemented on a solar collectors field (Juuso *et al.*, 1997). Later adaptive set point procedure and feed forward features have been included for avoiding overheating. The present controller takes also care of the actual set points of the temperature (Juuso and Valenzuela, 2003).

Models have been integrated to various control schemes. Feedforward approaches based directly on the steady state energy balance relationships can use measurements of solar radiation and inlet temperature (Camacho *et al.*, 1992). 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). The adaptation scheme of LE controllers is extended by a model-based handling of the operating conditions (Juuso and Valenzuela, 2003).

## 3. MODELLING AND SIMULATION

Trial and error type controller tuning does not work since the operating conditions cannot be reproduced or planned in detail because of changing weather conditions. As the process must be controlled all the time, modelling is based on process data from controlled process.

### *3.1 Working point model*

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

$$I_{eff}A_{eff} = (1-\eta_p)F\rho c T_{diff} \tag{1}$$

where $I_{eff}$ is effective irradiation ($Wm^{-2}$), $A_{eff}$ 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 $T_{diff}$ temperature difference between the inlet and the outlet ($^oC$). The effective irradiation is the direct irradiation modified by taking into account the solar time, declination and azimuth.

A simple feedforward controller

$$F = \alpha \frac{I_{eff}}{T_{out} - T_{in}} \tag{2}$$

can be obtained by combining the oil characteristics and geometrical parameters into a term

$$\alpha = \frac{A_{eff}}{(1-\eta_p)\rho c}. \tag{3}$$

The linguistic equation (LE) approach extends these ideas with nonlinear data-driven models. LE models consist of two parts: *interactions* are handled with linear equations, and nonlinearities are taken into account by *membership definitions.* The membership definition is a nonlinear mapping of the variable values inside its range to the range $[-2, 2]$. (Juuso, 1999; Juuso, 2004*b*).

During the start-up 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

$$\tilde{T}_{diff} = \frac{0.20493\tilde{T}_{amb} + 0.50176\tilde{I}_{eff} + 0.33328}{0.77147}, \quad (4)$$

where $\tilde{T}_{diff}$, $\tilde{T}_{amb}$ and $\tilde{I}_{eff}$ are values obtained by nonlinear scaling of variables $T_{diff}$, $T_{amb}$ and $I_{eff}$, correspondingly.

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. This type of model can be used for feedforward control but the chosen control strategy will effect to the coefficients.

### *3.2 Dynamic LE model*

Dynamic simulators are needed in controller design and tuning. Conventional mechanistic models do not work: there are problems with oscillations and irradiation disturbances. Data-driven multivariable modelling with understanding of the process can be done with fuzzy set systems and linguistic equations (Juuso, 2004*b*).

The basic form of the *LE* model is a static mapping, and therefore dynamic *LE* models could include several inputs and outputs originating from a single variable (Juuso, 1999). The coefficients are shown in Table 1. The new temperature difference between the inlet and outlet depends on the irradiation, oil flow and previous temperature difference.

Table 1. Interaction coefficients of a dynamic LE model for the temperature difference.

| Variable | | Coefficient |
|---|---|---|
| Oil Flow | $F$ | -0.19012 |
| Effective irradiation | $I_{eff}$ | 0.31697 |
| Temperature difference | $T_{diff}(t)$ | 0.52315 |
| Temperature difference | $T_{diff}(t+\Delta t)$ | -0.76128 |
| Bias | B | 0.10073 |

The dynamic simulator of the solar collector field represents very accurately the field operation. Oscillatory conditions are also handled correctly although the dynamics depends on the operating point. Usually, the multimodel 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. According to the tests, the fuzzy LE system with four operating areas is clearly the best overall model (Juuso, 2003).

For start-up 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 radiation disturbances, the LE simulator operates quite well: the temperature is on the appropriate range all the time and the timing of the changes is very good. For handling special situations, additional fuzzy models have been developed on the basis of the Fuzzy–ROSA method. For the period after radiation disturbances, the combined model improves the result considerably. (Juuso *et al.*, 2000).

### *3.3 Distributed parameter models*

Distributed parameter model can be based on the energy balance: energy stored = Irradiance - Energy transferred - Heat loss. For a unit volume this can be represented by

$$\rho c A \frac{\partial T}{\partial t} = I_{eff} W \eta_0 - \rho c F \frac{\partial T}{\partial x} - hD(T - T_{amb}) \quad (5)$$

where $A$ is cross section of the pipe line ($m^2$), $c$ specific heat of oil ($Jkg^{-1}K^{-1}$), $D$ pipe diameter ($m$), $I_{eff}$ irradiation ($Wm^{-2}$), $h$ heat transfer coefficient ($Wm^{-2}K^{-1}$), $T$ oil temperature ($^oC$), $T_{amb}$ ambient temperature ($^oC$), $x$ length coordinate ($m$), $F$ flow rate ($m^3s^{-1}$), $W$ width of the mirror ($m$), $\eta_0$ optical efficiency, $\rho$ oil density $kgm^{-3}$, $t$ time ($s$). Oil properties depend drastically on temperature, and therefore operating conditions change considerably during the working day, e.g. during the start-up stage, the oil flow is limited by the high viscosity.

In distributed parameter models, the collector field is divided into modules, where the dynamic LE models are applied in a distributed way (Juuso, 2004*a*). Equation (5) is represented by

$$\frac{\Delta T}{\Delta t} = a_1\tilde{I}_{eff} + a_2\tilde{T}_i(t) + a_3\tilde{T}_{amb} + a_4\tilde{F}, \quad (6)$$

where coefficients $a_1$, $a_2$, $a_3$ and $a_4$ depend on operating conditions, and therefore, the process is highly nonlinear. As this model is based on nonlinear scaling of variables, the corresponding coefficients are constant on a wide operating area. Location of the *ith* element depends on the flow rate.

In cloudy conditions, the heating effect can be strongly uneven. These effects are simulated by introducing disturbances into the irradiation. The flow rate depends also on the density that is decreasing with increasing temperature. Uneven distributions of the oil flow are important if the oil flow changes are rapid since some loops may be unable to follow.

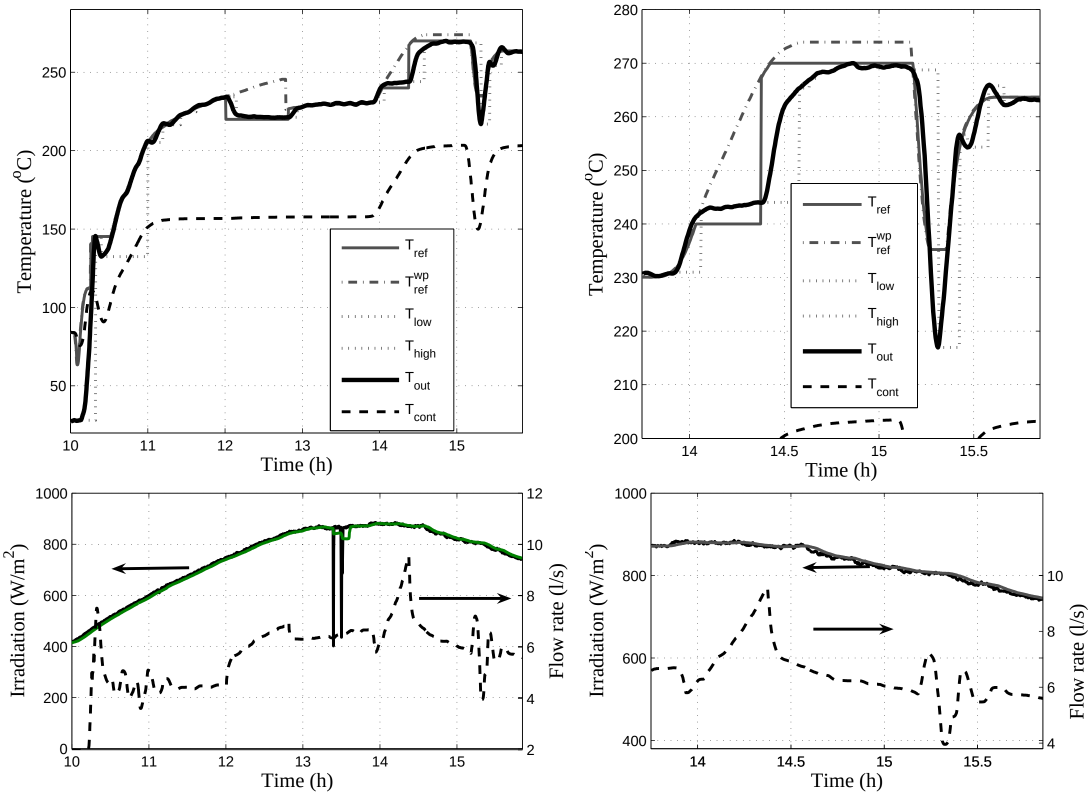

Fig. 2. Test results of the Linguistic Equation Controller: temperatures, oil flow and irradiation.

## 4. MULTILEVEL 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.

### *4.1 Linguistic equation controller*

The basic controller is a PI-type LE controller is represented in the following form

$$\Delta u = e + \Delta e, \tag{7}$$

which is a special case of the matrix equation $AX = 0$ with the interaction matrix $A = [\,1\ 1\ {-1}\,]$, and variables $X = [\,e\ \Delta e\ \Delta u\,]^T$. The error variable is the deviation of the outlet temperature from the set point, and the control variable is oil flow. Nonlinear scaling is done for the values of $e$ and $\Delta e$ , and after applying the control equation (7) the resulting change of control is scaled back to real scale.

The first LE controller based on Eq. 7 was already an efficient solution for normal operating conditions close to the solar noon (Fig. 2). However, it had oscillation problems in the start-up phase conditions since the changes of control was too large if the temperature difference $T_{diff}$ was high compared to the irradiation level (Juuso *et al.*, 1997).

### *4.2 Predefined adaptation*

Oscillations are considerably reduced by modifying the operation of the controller by an equation

$$WP = \tilde{I}_{eff} - \tilde{T}_{diff}, \tag{8}$$

where $\tilde{I}_{eff}$ is the scaled value of the effective solar irradiation and $\tilde{T}_{diff}$ the scaled value of the temperature difference between inlet and outlet temperatures were used. In the normal working point ($wp = 0$), the irradiation $\tilde{I}_{eff}$ and the temperature difference, $\tilde{T}_{diff}$, are on the same level. High working point ($wp > 0$) means low $\tilde{T}_{diff}$ compared to the irradiation level $\tilde{I}_{eff}$. Correspondingly, low working point ($wp < 0$) means high $\tilde{T}_{diff}$ compared to the irradiation level $\tilde{I}_{eff}$.

The operation condition controller changes the control surface of the basic LE controller by modifying membership definitions for the change in the control variable $\Delta u$. On a clear day (Fig. 2) the working point was normal ($wp = 0$) during the start-up phase and high ($wp = 1$) in the afternoon (Fig. 3). On a cloudy day (Fig. 4) the working point was kept normal throughout the day. To avoid oscillations the working point was kept positive.

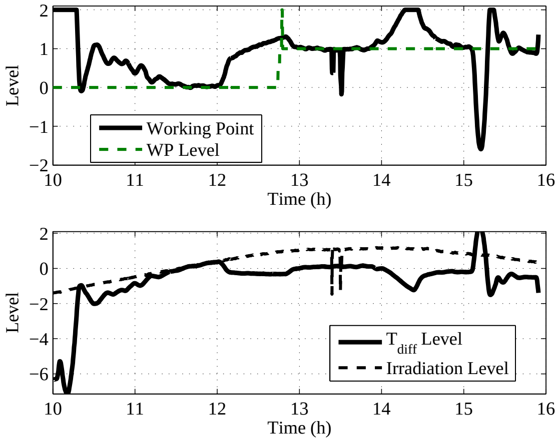

Fig. 3. Working point control.

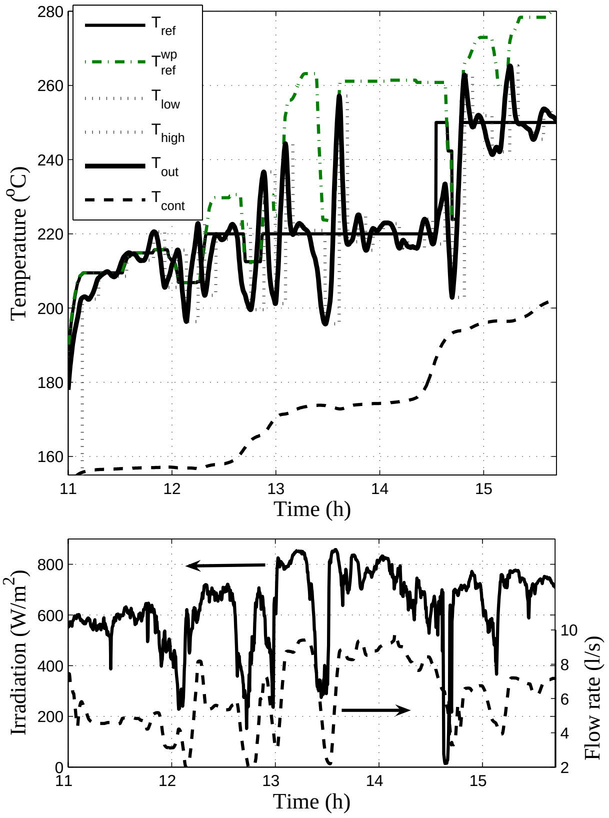

Fig. 4. Test results of the Linguistic Equation Controller on a cloudy day: temperatures, oil flow and irradiation.

In addition to this a predictive LE controller changes membership definition for the derivative of the error $\Delta e$. This level contains both the braking and unsymmetrical action (Juuso, 1999). These features are sufficient if irradiation conditions are changing smoothly and if the start-up is kept on moderate temperatures. The predefined adaptation can be improved considerably by using dynamic LE models in the tuning phase.

### *4.3 Smart control*

Too high temperatures are usually results of following cases:

- The inlet temperature changes considerably from the average level corresponding to case known to the controller;
- Temperature is rising so fast that the controller cannot handle efficiently the evolving situation;
- The temperature difference between the inlet and the outlet is too high compared to acceptable level corresponding to the recent average of the corrected irradiation.

Additional change of control is introduced if at least one of these cases is active. The main purpose is to avoid oscillatory conditions as delays make it difficult to damp oscillations with feedback control. The first two actions are predictive, and the third one is corrective. All these properties are implemented into a very compact control program. Modularity is beneficial for the tuning of the controller to various operating conditions, and most important is that the same controller can operate on the whole working area. These smart features can be considered as feedforward controllers which are activated for a short time when needed.

These smart control actions are beneficial in smooth compensation of load disturbances without exceeding the safety limits of the collector system (Fig. 2). Their tuning can be improved by distributed parameter models.

### *4.4 Cascade control*

Earlier the working point model made the control surface steeper or flatter but in the present controller it is even more important. In the present controller it affects to the set point as well. The set point is reduced if the irradiation or the inlet temperature is staying on a lower level long time (Juuso and Valenzuela, 2003).

Cascade control is used in the start-up to facilitate fast temperature increase without oscillatory behaviour (Fig. 2). Similar reduction of the set point is activated for load disturbances (Fig. 2). In cloudy conditions the cascade control reduces considerably the overshoot after clouds (Fig. 4).

The multilevel controller can handle efficiently even multiple disturbances. Adaptive set point procedure and feedforward features are essential for avoiding overheating. The new adaptive technique has reduced considerably temperature differences between collector loops. Efficient energy collection was achieved even in variable operating condition (Fig. 5).

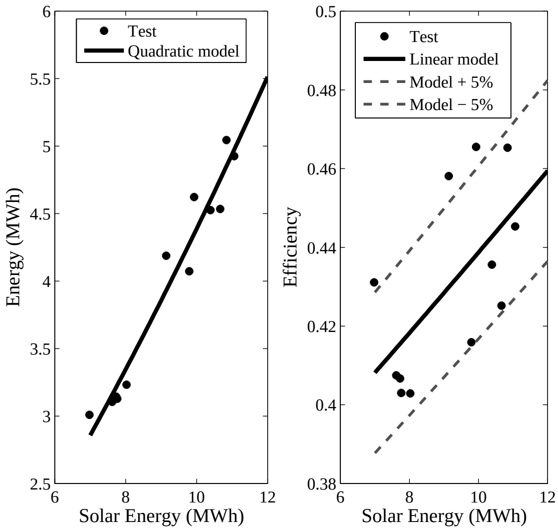

Fig. 5. Results of the energy collection during the test campaign (June 4 - 21, 2002): energy and efficiency.

## 5. CONCLUSIONS

Various nonlinear features are adapted to changing operating conditions with predefined adaptation techniques. Tuning with different lumped and distributed parameter models improve performance of the controllers. The new adaptive control technique has reduced considerably temperature differences between collector loops. Efficient energy collection was achieved even in variable operating condition.

## REFERENCES

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

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

Farkas, I. and I. Vajk (2002). Internal model-based controller for a solar plant. In: *CD-ROM Preprints of the 15th Triennial World Congress.* 6 p. IFAC.

Juuso, E. K. (1999). Fuzzy control in process industry: The linguistic equation approach. In: *Fuzzy Algorithms for Control, International Series in Intelligent Technologies* (H. B. Verbruggen, H.-J. Zimmermann and R. Babuska, Eds.). pp. 243–300. Kluwer. Boston.

Juuso, E. K. (2003). Intelligent dynamic simulation of a solar collector field. In: *Simulation in Industry, 15th European Simulation Symposium ESS 2003.* pp. 443–449. SCS, Gruner Druck. Erlangen, Germany.

Juuso, E. K. (2004*a*). Dynamic simulation of a solar collector field with intelligent distributed parameter models. In: *Proceedings of SIMS 2004 - the 45th Scandinavian Conference on Simulation and Modelling.* pp. 141–153. DTU. Lungby, Denmark.

Juuso, E. K. (2004*b*). Integration of intelligent systems in development of smart adaptive systems. *International Journal of Approximate Reasoning* **35**, 307–337.

Juuso, E. K. and L. Valenzuela (2003). Adaptive intelligent control of a solar collector field. In: *Proceedings of Eunite 2003 - European Symposium on Intelligent Technologies, Hybrid Systems and their implementation on Smart Adaptive Systems.* pp. 26–35. Wissenschaftsverlag Mainz. Aachen.

Juuso, E. K., D. Schauten, T. Slawinski and H. Kiendl (2000). Combination of linguistic equations and the fuzzy-rosa method in dynamic simulation of a solar collector field. In: *Proceedings of TOOLMET 2000 Symposium - Tool Environments and Development Methods for Intelligent Systems.* Oulun yliopistopaino. Oulu. pp. 63–77.

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

Juuso, E. K., P. Balsa and L. Valenzuela (1998). Multilevel linguistic equation controller applied to a 1 mw solar power plant. In: *Proceedings of the ACC'98.* Vol. 6. ACC. pp. 3891–3895.

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

## ACKNOWLEDGEMENTS

All the experiments were carried out within the projects "Innovative Training Horizons in Applied Solar Thermal and Chemical Technologies"(C.N: ERBFMGECT950023) and "Improving Human Potential Programme - Access to Research Infrastructures Activity" (C.N: HPRI-CT-1999-00013) supported by the DG XII. The combined modelling research was sponsored by the Deutsche Forschungsgemeinschaft (DFG), as part of the Collaborative Research Center Computational Intelligence (531) of the University of Dortmund.