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INTERNAL MODEL-BASED CONTROLLER FOR A SOLAR PLANT

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Abstract: In this study a model-based control designed for the operation of a solar power plant is discussed. The simplified physically based model of the plant was developed on the basis of the energy balances including the solar insulation as an input, the heat transferred by the flow of the oil as a working media and the overall heat loss from the plant. The outlet temperature of the collector field is the reference/set-point value while the volumetric flow rate of the oil is the manipulating variable to the controller. The solar radiation, the ambient temperature and the inlet oil temperature to the collector field are assumed as the disturbances. The model developed and identified is an internal part of the controller. The initial control experimental results are also presented. *Copyright © 2001 IFAC*

Keywords: Solar power plant, physically-based model, identification, internal model control (IMC).

1. INTRODUCTION

The distributed collector field of parabolic mirrors are to be used as a heat power plant of solar energy. In a system like that as because of the high temperature usually oil is circulating through the collector filed and absorbing the solar irradiation. Due to the possible insulation level a heat loss is occurring from the system. The rest of the irradiated solar energy is gained towards to a storage tank and used for further technological heat processing. The objective of the solar plant control is to maintain the outlet oil temperature in order to get an appropriate value taken back to the storage tank and achieving the best thermal efficiency of the system.

Several control approaches were applied to fulfil the efficiency requirements of the plant that is non-linear and additionally it has a fairly long time delay in the system. Camacho et al. (1997) gave an overview of many possible control strategies to be applied, as basic feed-forward and PID control schemes, adaptive control, model-based predictive control (MPC), frequency domain and robust optimal control and also fuzzy logic control.

Due to the non-linearity the adaptive controllers (Coito et al, 1997 and Silva et al., 1998) could be used to overcome this the unpredictable change in the plant. However a problem may appear with the identification which can be long due to the fast changes in the system.

Another solution is to overcome the non-linear control problem of a solar plant is to use predictive controllers (Pickhardt et al., 1998 and Neves da Silva, 1999). In this case it could be also a problem with the long calculation time concerning to the future trajectory of the manipulated variable.

Self-tuning control of the solar plant (Camacho et. al, 1992) based on a pole assignment can be also a solution especially if it incorporates serial feedforward elements to cope with the measurable external disturbances.

In the recent study an internal model controller (IMC) of the solar plant is designed and discussed where the simplified non-linear model of the plant has been developed on the basis of physical phenomena.

2. DESCRIPTION OF THE SOLAR PLANT

The solar power plant studied in this paper is located in Tabernas (Almeria), Spain. The picture of ACUREX collector field and the storage tank can be seen in Fig. 1.

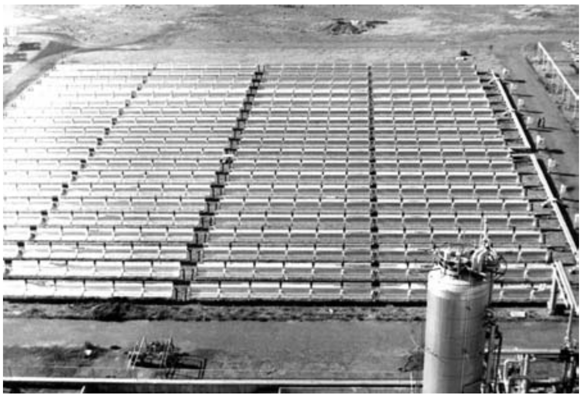

Fig. 1. Picture of the solar plant

The collector filed consists of 10 parallel loops laying in an east-west axis. Each loop is arranged in 2 return rows consisting of totally 48 individual collectors. The total length of one loop is 172 metres of which 142 metres are the active part. Six collectors are organised in one common tracking group operated by the same mechanism to orient into optimal position of the mirrors to the sun in order to provide maximum amount of irradiation income. The collectors are made up reflective cylindrical surfaces in order to concentrate the solar irradiation onto the pipe positioned on the focal line of the parabolic surface. The absorbed solar energy is transferred by pumping oil through the collector pipe into a storage tank. The volume of the storage tank is about 140 m^3. In the system Santotherm 55 type of oil is used allowing working temperature up to 300 °C without any decomposition effect.

The operating scheme of the plant along with the main sensors is illustrated in Fig. 2.

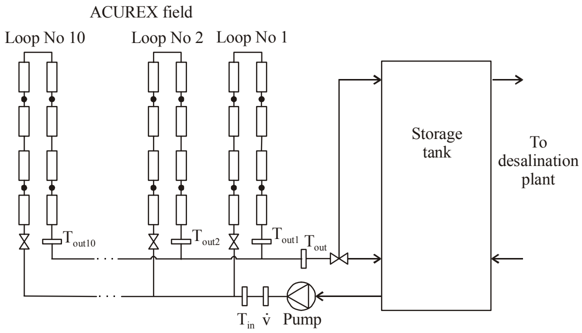

Fig. 2. Schematic layout of the solar plant

Normally, the inlet oil taken back to the storage tank is positioned to the top part. However, in the case of lower outlet oil temperature that especially occurs during the morning tracking period, the oil could be pumped to the bottom of the storage tank avoiding to destroy the developed thermal stratification in the tank. The heat energy of oil stored in the tank could be used for a desalination plant process and other technological purposes, as well.

In the system, beside the common inlet and outlet oil temperatures of the collector array the outlet oil temperatures of each collector loop are measured individually. The ambient temperature, the global solar radiation and the oil flow rate are also measured and used for the control purposes.

The main control target is to keep the outlet oil temperature at a set-point value by manipulating the oil flow with the help of a pump. Due to safety reasons, however, the oil flow rate is limited in the range of 2-10 litres per second.

3. MODELLING OF THE SOLAR PLANT

To describe the thermal behaviour of the distributed collector field and appropriate physically based model seems to be the most appropriate to apply. Camacho et al. (1997) used a 100 lumped parameter sub-models taking into account the sun position, the field geometry, the mirror reflectivity, the solar radiation and the inlet oil temperature as well. Their model includes separate equations for the oil as a working media and also for the absorption tube providing to calculate the temperature distribution at a given time along with the collector length.

For control purposes, however, simpler models can also be applied successfully (Neves da Silva, 2000).

In the case of control applications the most important consideration is to describe the outlet oil temperature as a function of the flow rate of the oil at a reasonably accurate level. Such a model, based on the energy balance, could be formed in the following way:

Energy stored = Irradiance - Energy transferred - - Heat loss. (1)

Applying the energy conservation low for a length control volume of dx over a time interval $d\tau$ the actual equation can be set up as:

$$\rho\, c\, A \frac{\partial T}{\partial \tau} = I\, W\, \eta_0 - \rho\, c\, \dot{v} \frac{\partial T}{\partial x} - h\, D \left(T - T_{amb}\right), \tag{2}$$

where:

- A - cross-section of the pipe line (m^2),
- c - specific heat of oil (J/kgK),
- D - pipe line diameter (m),
- I - solar radiation (W/m^2),
- h - overall heat loss coefficient (W/m^2K),
- T - oil temperature (°C),
- T_{amb} - ambient temperature (°C),
- x - length co-ordinate (m),
- $\dot{v}$ - volumetric flow rate of oil (m^3/s),
- W - width of the mirror (m),
- η_0 - optical efficiency,
- ρ - oil density (kg/m^3),
- τ - time (s).

For the solution of the model described partial differential equation a finite element method was chosen.

The oil flowing in the tube is divided into N discrete elements, and the model follows the thermal behavior and the movement along the length of the collector for each finite elements of the oil. Using this conditions, it means that each element of oil are characterized with two parameters of which one is the temperature and the second one is its relative position in the collector.

The thermal state of the *i-th* element is updated by the equation of:

$$T_i(\tau + \Delta\tau) = T_i(\tau) + (\alpha I(\tau) - \beta(T_i(\tau) - T_{amb}(\tau)))\Delta\tau, \tag{3}$$

where $\Delta\tau$ is the sampling time. The model has two significant parameters, the first one is connected the efficiency of the radiation (α), the second one is associated with the thermal loss (β). The initial conditions are determined by the inlet oil temperature.

The movement of a finite element along the total length of the collector loop (L) is followed by the normal kinematics way. The position of the *i-th* element in relative unit (x=x/L) is calculated by

$$x_i(\tau + \Delta\tau) = x_i(\tau) + \Delta t\ \dot{v}(\tau) / V_{tot}. \tag{4}$$

4. CONTROL DESIGN

In this study, in order to solve the temperature control of the described solar plant an internal model-based controller was considered.

The internal model control is a very often used control strategy for linear systems. One of its classical forms is shown in Fig. 3 where P is the process, M is the model of the process and Q is the IMC controller. This IMC and the classical feedback realization can generate the same loop characteristics. But if the process has dead time, the equivalent classical feedback controller has a non-traditional form.

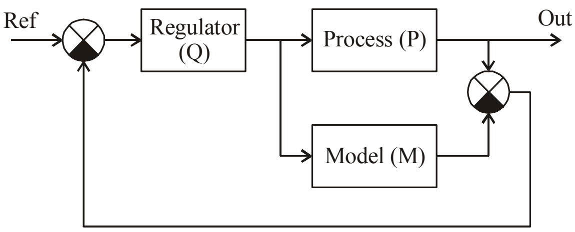

Fig. 3. Scheme of the IMC structure

The IMC design procedure generally consists of two steps: the feed-forward controller designed for the nominal model and the controller is tuned by an extra filter to meet the robustness requirements.

One of the advantages of the IMC structure is the following. If the process and the process model have the same transfer function, that is no model-plant mismatch, the IMC controller becomes effectively open loop. So the design of Q is relatively simple. The controller designed on the basis of the nominal plant is directly obtained if the process is open-loop stable. The realizable inverse of the process model can give good control performance. It can be noted that the IMC controller is identical to the parameterization of all stabilizing Q. The controller can include a serial filter to change the behavior of the control loop.

If the model is not exactly same as the plant, the model-plant mismatch generates a feedback signal that can cause performance degradation or even instability. The serial filter is selected such a way to reduce the model-plant mismatch. One of the possible controller design strategies can be found in Morari and Zafiriou (1989).

The internal model control can be used for non-linear system as well. As it was shown in the previous section the solar plant can be modeled by non-linear partial differential equation. The dominant part of the process is the flow rate dependent delay time. The IMC can control efficiently the process even having varying delay time. The scheme of the applied time-delayed non-linear IMC is shown in Fig. 4.

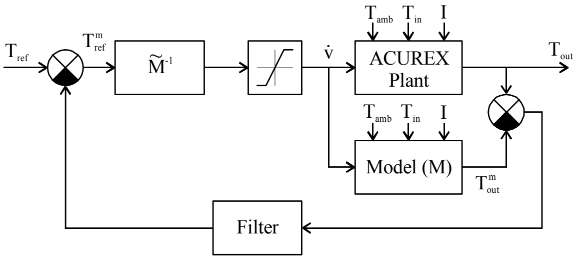

Fig. 4. Scheme of the internal model-based controller

The model (M) described in the previous section was used as a part of the control design along with its realisable inverse ($\tilde{M}^{-1}$). In the scheme the solar irradiance (I), the ambient (T_{amb}) and the inlet (T_{in}) oil temperatures are assumed as disturbances. The reference (set-point) temperature (T_{ref}) is the average outlet oil temperature of the collector loops. In the plant the outlet temperature of the collector array is available through measurements but for practical reason the loop average values are used for control. The Filter block is used for noise elimination.

On the basis of the control scheme shown in Fig. 4 the reference signal of the control is modified by the model mismatch:

$$T^m_{ref} = T_{ref} + (T^m_{out} - T_{out})\,. \qquad (5)$$

In order to express directly the control task the Eqs (2-5) were reorganised using the modified reference value. Hence, the control signal can be calculated with the following form:

$$\dot{v} = \left[\alpha\, I - \beta\left(\frac{T^m_{ref} + T_{in}}{2} - T_{amb}\right)\right]\frac{V_{tot}}{T^m_{ref} - T_{in}}\,. \qquad (6)$$

In Eqs (5-6) the following notations are used:

- T_{in} - field inlet oil temperature (°C),
- T_{out} - field outlet oil temperature (°C),
- T^m_{out} - outlet oil temperature of the model (°C),
- T_{ref} - set-point/reference temperature (°C),
- T^m_{ref} - the modified reference temperature (°C),
- V_{tot} - total amount of oil in the collector array (m^3),
- α - control parameter (m^2 °C/J),
- β - control parameter (1/s).

Taking into account the Eq (6) it can be seen that the realizable inverse of the model in this case is a static nonlinear function without any dynamics.

As it was already mentioned before, in this approach α refers to the energy input (solar radiation) to the system meanwhile β is associated with the overall heat loss of the system. Before carrying out real control experiments the control parameters were identified based on the simulation running with the help of the model developed.

5. EXPERIMENTAL RESULTS

The experiments were performed first in order to make final tuning of the control parameters. During the recent test α, the radiation gain parameter was identified with a value of 0,325 10^{-3} m^2 °C/J. Temporarily, β, the heat loss control parameter was assumed to be zero. In the following experiments the controller was used in such a simplified mode (one parameter model).

As a first example, the behaviour of the controller is shown under ideally selected circumstances, which means that there is no any fast changing in the disturbances, especially in the solar radiation. The control results of Test 1 are shown in Fig. 5. It is nice to observe that the outlet temperature reaches the set-point values without any overshooting.

As because of the nature of the controller it is very important to use as accurate model as possible. It is therefore valid also for the physical parameters of the model. Looking at the Eq. (6) it is clear that the total volume of the oil in the collector field has one of the greatest importance. That value can be calculated from the geometry of the pipe lines. It seems, however that more accurate value could be achieved experimentally. In Test 2, beside the control experiment the determination of the total oil volume is also performed. In this purpose the oil flow rates was changed in manual operation from 6 to 4 and back again to 6 litres per seconds (see in Fig. 6). The two-directional step-wise was applied to avoid the hysteresis and the resonance characteristics of the collector field especially could occur at lower oil flow rate (Meaburn and Hughes, 1993). From the time delayed step responses to these disturbances the total volume of the oil in the collector field was identified for 1820 litres.

In the Test 3 a control trial was carried out under very unfavourable radiation conditions caused by fast changing of clouds. Normally, in the control system of the solar plant the time delay is somewhere between 5-10 minutes depending on the actual flow rate. From the experiments it can be seen that under such disturbances physically no successful control could be realised (Fig. 7) for such a long time delayed system.

6. CONCLUSION

In this paper an internal model controller (IMC) of a solar plant was designed and tested. The IMC seems to be an ideal tool to control efficiently a process even having varying delay time.

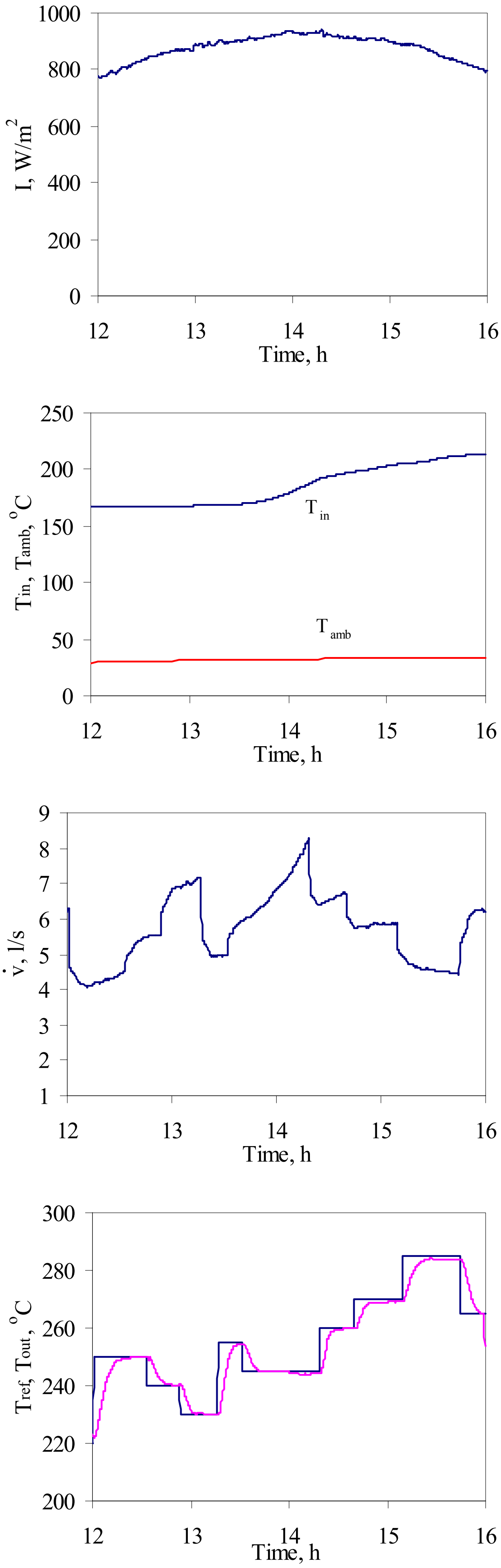

Fig. 5. Results of Test 1 (July 9, 2001)

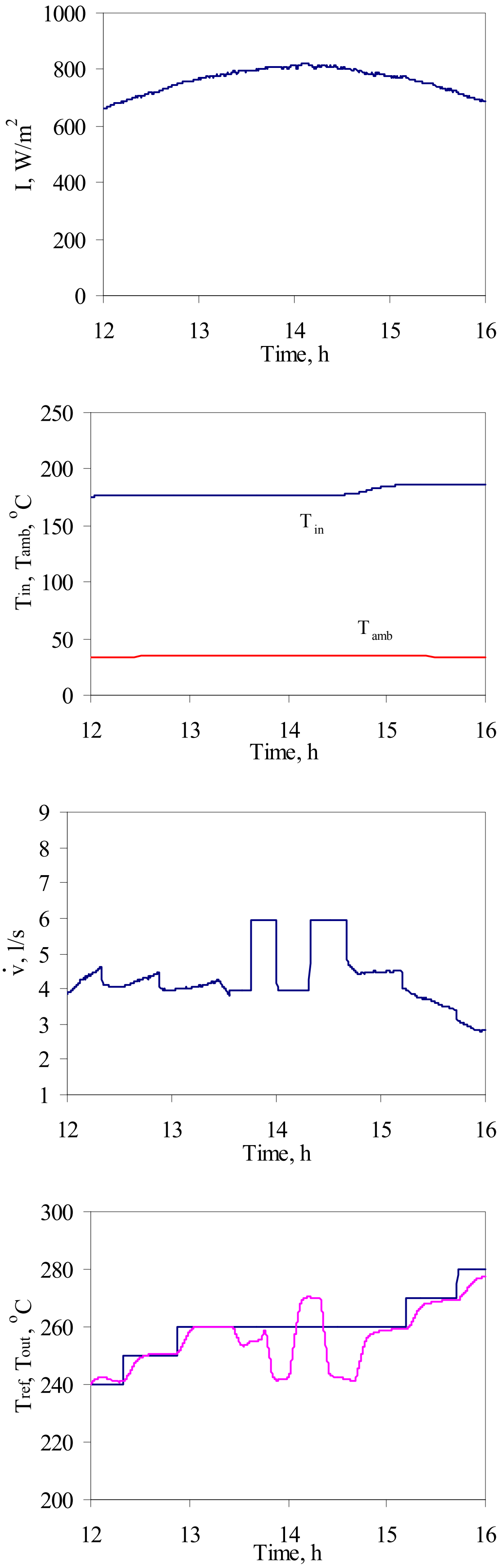

Fig. 6. Results of Test 2 (July 11, 2001)

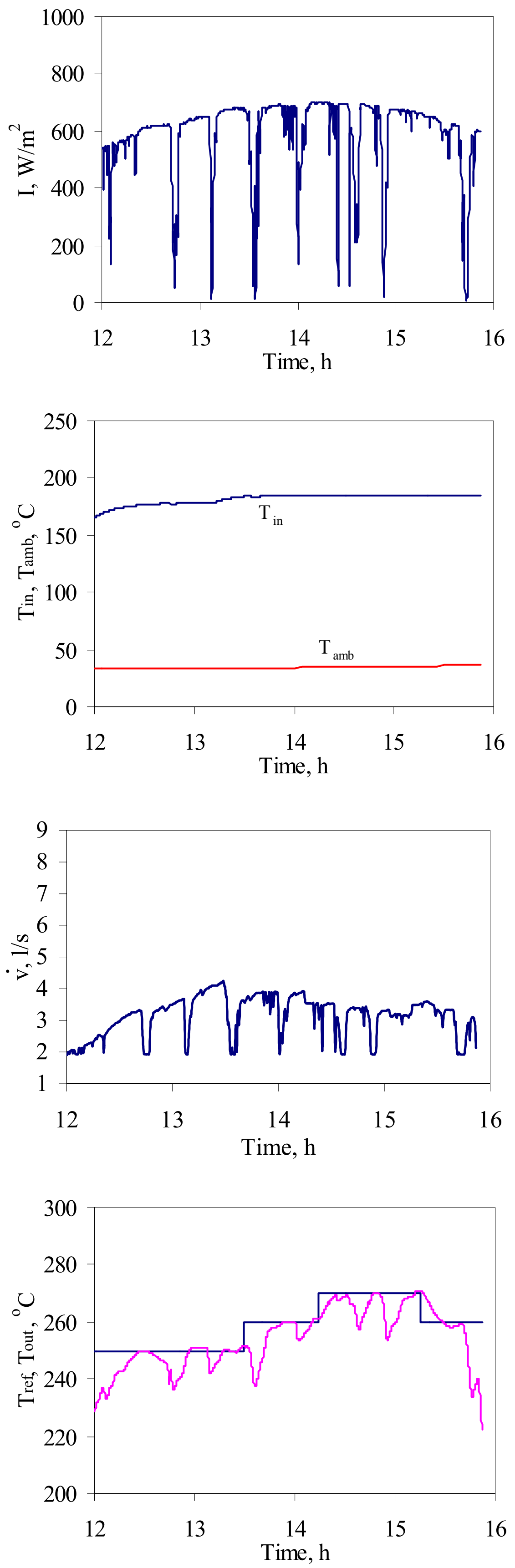

Fig. 7. Results of Test 3 (July 12, 2001)

It has been stated that a simplified physically based model can serve as a basis for control of a solar plant.

Energy balance of the solar collector field should involve the stored energy in the oil, the solar radiation input, the heat transfer by the oil and the heat loss from the system. The control equations were derived including the control parameters referring to solar radiation gain and heat loss.

Identification of the model and the control parameters were carried out via simulation running and control experiments designed for such purposes.

The one-parameter model is able to perform a good quality of control under ideal disturbance conditions. Extension with a second parameter can improve the efficiency of the control algorithms.

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REFERENCES

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 Control Systems.

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

Coito, F., J.M. Lemos and R.N. da Silva (1997). Adaptive control of a solar energy plant: exploiting acceptable disturbances, *International Journal of Adaptive Control and Signal Processing*, **11**, p. 327-342.

Meaburn, A. and F.M. Hughes (1993). Resonance characteristics of distributed solar collector fields, *Solar Energy,* **Vol. 51. No. 3.**, pp. 215-221.

Morari, M. and E. Zafiriou (1989). *Robust process control*. Prentice-Hall, Englewood Cliffs.

Neves da Silva, R. (1999). Time-scaled predictive controller of a solar power plant, Proceedings of the European Control Conference'99, Karlsruhe, Germany

Neves da Silva (2000), R. Plant Driven Design of a Nonlinear PID Controller, IFAC Workshop on Digital Control 2000, Teressa, Spain

Pickhardt, R. and R.N. Silva (1998). Application of a nonlinear predictive controller to a solar power plant, Proceedings of the 1998 IEEE Conference on control applications, Trieste, Italy.

Silva, R.N., N. Filatov, J.M. Lemos and H. Unbehauen (1998). Feedback/feedfoward dual adaptive control of a solar collector field, Proceedings of the 1998 IEEE Conference on control applications, Trieste, Italy.

Vajk, I. (1999). Sensitivity of nonlinear modelling, Proceedings of 14th World Congress of IFAC, Beijing, China, Volume H, p. 19-24.