Advanced automated algorithm generation software in the control of a solar power plant

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Abstract

The paper presents an application of techniques and methodologies of automatic control design - already developed and successfully experimented by EICAS in automatic control design - to the control of the ACUREX field of the Plataforma Solar de Almería (PSA). The application has been developed within the ACODUASIS Project aiming at transferring to the robotics sector the EICAS methodology by means of the high professional EICASLab software tool. The use of EICASLab along the design process of the control strategy may be of significant help. Moreover the tool was not developed for experts only, and in this way it helps even the designer without specific know-how. Its use is reflected in a reduction of time spent in the design phase and, consequently, in the increase of competitiveness.

Keywords: Automatic Control Design, Model Identification, Control Parameter Numerical Optimisation.

1 Introduction

The EICAS methodological approach has been developed along 20 years starting from the results obtained by Donati, Carlucci and Vallauri [1-2].

Of key importance are the notions of “plant”, “dynamic system” and “model”. A “Plant” is a physical object belonging to the real world. A “Dynamic system” is a mathematical object defined by an axiomatic concept (the definition formulated by R.E. Kalman in 1969 is adopted). A “Model” is a dynamic system used to describe the plant dynamic performance, the knowledge of which is necessary for developing the plant automatic control design.

Within the ACODUASIS IPS-2001-42068 project the EICAS methodology has been applied to the control of the ACUREX field of the Plataforma Solar de Almería (PSA), located in the south of Spain. This plant is characterized by having static gain and time constants directly dependent on the operating point, which is established by the manipulated variable, the flow. Thus, this facility has been used as a test bench for several control techniques applied by several research groups within Europe. The references [3-7] are some examples of that work. In this paper, the control design using the software tool named EICASLAB is presented together with some simulation results [8].

2 Eicas methodology

Models can give only an approximate description of the related plant dynamics, so that a plant-model uncertainty always exists, which causes an error $e(i)=y(i)-y_m(i)$ between the plant actual output $y(i)$ and the one $y_m(i)$ computed through the model (see Fig.1).

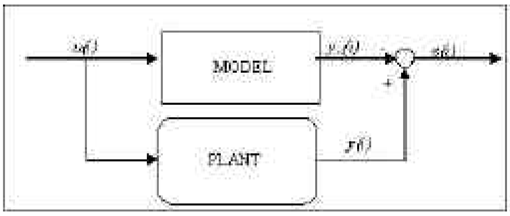

Fig. 1. Plant-model error

The plant-model uncertainty is said to be *"norm bounded"* if finite D and E exist, so that the following inequality holds

$$||y-y_m|| < E\,||y_m|| + D \qquad (1)$$

for any $u(i)$ belonging to the admissible input set U and for any plant operating condition within the set of the admissible operating conditions.

Let us assume that the plant-model uncertainty be *"norm bounded"* and let us build a plant state observer based on its model (see Fig. 2).

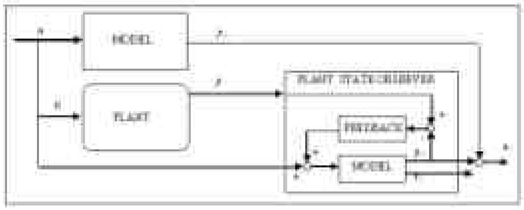

Fig. 2. Plant state observer

Let y_o be the observed output, coherent with the estimated state value x_o. Together with the inequality (1) also the following one holds:

$$||y_m-y_o|| < E_o\,||y_m|| + D_o \qquad (2)$$

for any $u(i)$ belonging to the admissible input set U and for any plant operating condition within the set of the admissible operating conditions: $E_o \leq E$, $D_o \leq D$.

Performing a suitable design of the state observer, plants exist which can be modeled by linear dynamic systems, satisfying the inequality (1) (norm bounded uncertainty) and the inequality (2) with the constraint $E_o < 1$ (accurate modeling within the required operating field). Such plants are called *"almost-linear plants"*: let us note that the above definition presumes that both a linear model and a related state observer have been defined and associated with the plant, complying with the above uncertainty constraint. The following theorem holds [2].

Theorem. Given an *"almost-linear plant"*, if a state controller H exists, which, in the absence of any plant-model uncertainty, can attenuate the effect - caused by an additive disturbance e on the observed output y_o - by a factor Q, "which can be made as small as required", then the same state controller H applied to the "*almost-linear plant*" attenuates the closed loop plant - model uncertainty effects so that the closed-loop error $e_o(i) = y_d(i)-y_o(i)$ between the observed and the required plant outputs satisfies the constraint:

$$||\,e_o\,|| < Q^*(\,E_o\,||\,y_d|| + D_o\,) \qquad (3)$$

being

$$Q^* < Q/(\,1- E_o(\,1+ Q))$$

the closed-loop error $y_d(i)$-$y(i)$ between the actual and the required plant outputs has an upper guaranteed finite bound.

3 Test case description: ACUREX Field

3.1 Plant description

The ACUREX field of the Plataforma Solar de Almería (PSA) is located in the south of Spain and consists of 480 distributed solar collectors, arranged in 10 loops along an east-west axis (Fig. 3 and 4). The collector has a reflective cylindrical parabolic surface, in order to concentrate the incident solar radiation on a pipe located on the surface focal line (fig. 5).

Fig. 3. The Acurex field

A heat transfer fluid (oil) is pumped from the bottom of a storage tank through the collectors, where it acquires solar energy, and from the output of the field again to the top of the tank. By manipulating the oil flow, with the pump, it is possible to control the output temperature of the oil.

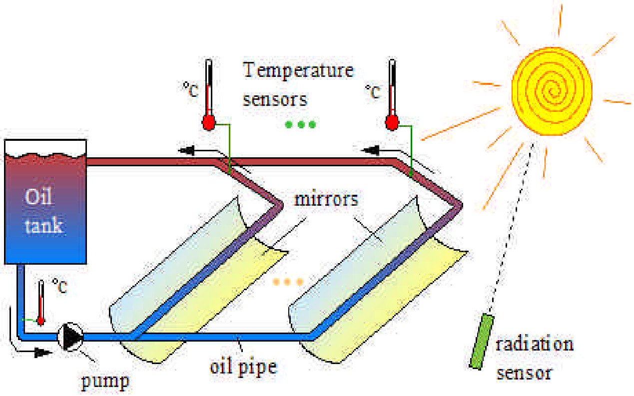

Fig. 4. Scheme of the plant

The controlled variable is computed from the average values of an array of 10 temperature sensors located at the output of each loop. Due to safety reasons, the oil flow is limited between 2.0 and 10.0 liters per second. The heated oil from the collector field, stored in the tank, can be used e.g. for the production of electrical energy or for the operation of a desalination plant.
The field is equipped with a tracking system by which the mirrors can rotate parallel to the axis of the receiving tube, in order to follow the sun in height throughout the day. There is a temperature sensor located at the input of the field, measuring the temperature of the oil entering the active part (mirrors).

Fig. 5. Cylindrical parabolic collector (with detail view)

3.2 Fine model of the plant

The plant is a distributed system where the most relevant part of the dynamics is the transport effect. Therefore, the plant should be modelled by a hyperbolic type equation which models transport phenomena with variable transport speed and a distributed source:

$$\frac{\partial y(z,t)}{\partial t}+\frac{f(t)}{A}\frac{\partial y(z,t)}{\partial z}=\Gamma w(t) \qquad (3)$$

where y is the temperature distribution along space z and time t, f is the volumetric flow and w is the effective solar radiation. The parameter $\Gamma=(Dh_o)/(rS_f A)$ (where D is the mirrors width, $?_0$ is the optical efficiency, A is the transversal pipe section area, S_f is the specific thermal capacity of the oil and ? is the oil density approximated by a constant) has been estimated using real plant data.

In the general case of equation (3), since the r.h.s. is independent of y, the solution can be found using the chain rule of derivation to integrate the collected solar radiation along the characteristic curve given by:

$$z(t)=\frac{1}{A}\int_{t_0}^{t} f(s)ds + z_0 \qquad (4)$$

yielding for the temperature at the output $z=L$

$$y(L,t)=J\cdot y(0,t_0)+\Gamma\int_{t_0}^{t} w(s)ds \qquad (5)$$

with the transport time $t = t - t_0$, given by

$$\int_{t-t}^{t} f(s)ds = L\cdot A = V \qquad (6)$$

where V is the total collector volume. The parameter J in equation (5) has been introduced in order to take the losses into account. Since the losses in this plant are not significant, this parameter arises as a simplification of the problem (the losses depend on the residence time *i.e.* the flow).

The equations (5) and (6) allow us to establish a steady-state relationship among the I/O temperature gain, $?T$,the solar radiation W and the flow F as

$$\Delta T=(\Gamma\cdot V)\cdot\frac{W}{F} \qquad (7)$$

3.3 Fine model validation results

Figures 6 shows superimposed results of the open-loop model and the real plant.

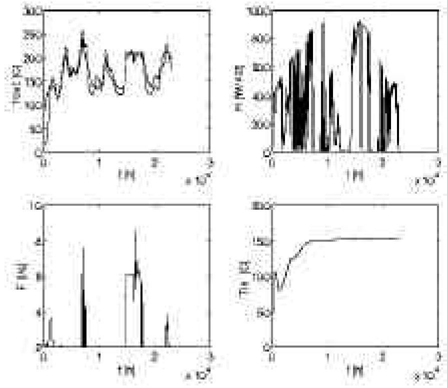

Fig. 6. Validation results I.

3.4 Plant characteristics

The plant characteristics interesting for control purposes are summarized as follows:

Plant output variables:

- The average of the temperature at the output of each loop, T_{out}. Other research works with this plant have been developed controlling the highest loop temperature. In that case, the control action is performed over only one loop, the most efficient one.
- The temperature at the input of the tank, T_{tnk}.

Manipulated variable:

- The oil flow command, F, to the local pump controller. This local controller is not accessible for parameterization of its gains.

Accessible disturbances:

- The value of the direct solar radiation, W.
- The temperature at the output of the tank, i.e. at the input of the field, T_{inp}.

Non accessible disturbances:

- The lost of tracking of the solar collectors.
- Difference between the solar radiation measured by the sensor and the one incident on the field. This difference should be bigger if the clouds are dispersed.
- The slow dust deposition over the mirrors surface, reducing its reflectivity, and the consequent wash by the plant operators or by the rain occurrence.
- Others.

Control goal:

- The controller should be able to follow a reference value (set point) of temperature together with a good disturbance rejection.

4 Control design using EicasLab

4.1 Analysis of the control design requirement specifications

According to the EICAS approach, as first step the control frequency band has been stated on the basis of the control design requirement specifications. Then the control sampling rate and the frequency band of the state observer have been derived.

4.2 Simplified model for EICASLab

For the system control design the following model has been used (fig. 7):

$$\frac{d\Delta T}{dt} = u + bW - a \cdot \Delta T \cdot F \qquad (8)$$

This model has been derived by considering the energy balance of each loop:

- the input power is proportional to the radiation W;
- the output power is due to the flow of the oil (that causes a loss of thermal energy because hot oil is substituted by cold oil) and it is proportional to the flow (F) and the difference of temperature between the input and the output (ΔT);
- the variation of ΔT is proportional to the variation of the energy of the loop.

The perturbations of the system and model errors have also been taken into account by introducing the disturbance (u), which has been modelled by a second order dynamic system.

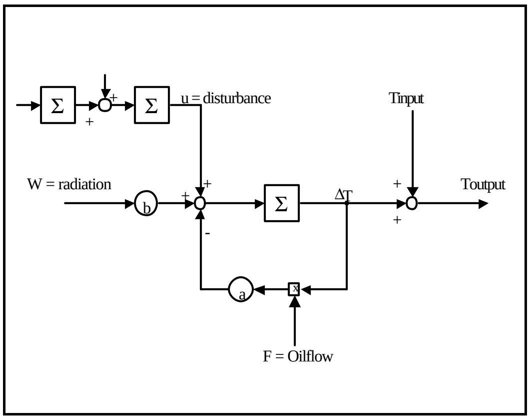

Fig. 7. Simplified model

4.3 The fine model

The model described in Eq. 3 to 6 has been considered sufficiently accurate and selected as the fine model.

4.4. The system state observer and the identification

A system state observer of the plant including the disturbances model acting on the plant has been built, as represented in Fig. 8.

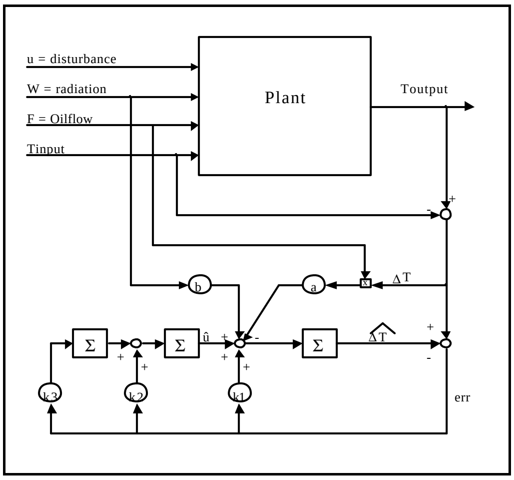

Fig. 8. Plant observer

The condition of almost linear plant has been verified through the identification of the simplified model parameters, by using the Identification feature of EICASLAB.

Figure 9 shows the results of the validation test of the identified parameters. It represents the comparison between the output of the identified system during this simulation and the output of the system to identify (the fine model in this case) and completely confirms the goodness of the used state observer.

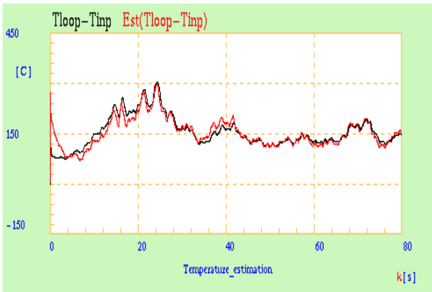

Fig. 9. Validation test for identified parameters

4.4 Implementation of the control in EICASLab

The control contains the observer described above and uses the estimation of the disturbances $\hat{d}$ to set the flow as follows (equation deriving from the steady state condition):

$$F = \frac{b \cdot W + \hat{d}}{a\left(T_{ref} - T_{inp}\right)}$$

where a and b are the identified parameters; T_{ref} (yr1 in the scheme above) is the desired temperature at the end of the loop; T_{inp} (INLETTEMP in the scheme above) is the temperature of the oil at the beginning of the loop; W is the sun radiation.

5 Simulation results

A test has been carried out by imposing a staircase reference as a desired temperature. The control results obtained by means of the EICASLab software tool are shown in figure 10. On top the behaviour of the oil flow is represented. On the bottom the true temperature is compared with the desired one, which is very well followed.

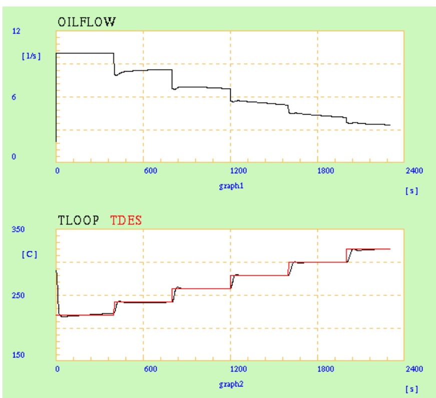

Fig. 10. Results with EICAS methodology

The performance appears fully compliant with the requirement specifications. The above results are compared with a linear PID controller whose operating point is established by the flow value since it is directly responsible for the static gain and bandwidth of the process. Due to the nonlinear characteristic of the plant, a PID controller tuned to perform in a middle flow value (e.g. 4.5 l/s) has poor results for lower or higher values of the flow within the operating range. Figure 11 shows simulation results illustrating this fact.

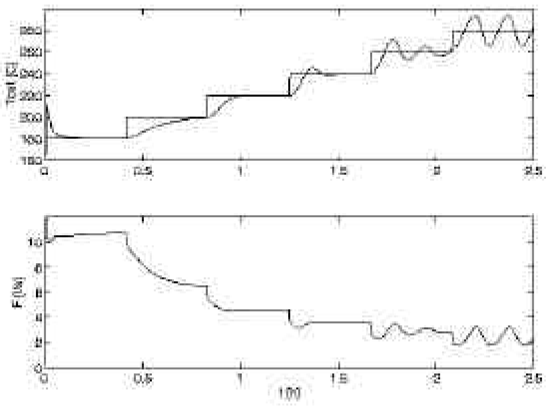

Fig. 11. Control results with a linear PID controller

6 Conclusions

This paper presents the application of the EICAS methodology, through the use of the EICASLab software tool, to the control of a solar plant as a test case. The necessary steps for the control design are here stated and some simulation results with the plant fine model are shown, illustrating its potentialities.

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