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Simulations in Development of Nonlinear Control for a Solar Thermal Power Plant

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Abstract:
This paper focuses on the utilization of dynamic simulation models in the planning of experiments for control development. A set of models based on the first principles for system level simulation of the complete new TCP-100 research facility at Plataforma Solar de Almería (CIEMAT) was planned for the development of control solutions for this new research facility which replaced the 32-year-old ACUREX facility. Many advances in Automatic Control have been reached by using the ACUREX field. Simulation experiments with the parabolic trough (PTC) field would require more tuning and adaptive parts before getting the required experimental data for typical operating conditions. The analysis operates for all state variables, which are temperatures, and input variables, which include solar radiation, ambient temperature and several setpoints. The nonlinear scaling approach keeps the algorithms unchanged by focusing on the meanings of the measured variables. The scaling functions are variable specific. For the irradiation, the functions do not change which means that also the indicator of the cloudiness remains the same. The algorithms are not changed and the data analysis is for a limited set of measurements and subsystems. The simulation experiments need to be first focused on the loops and modules of the solar field and the full model need to be extended before going to the full simulation tests and the test campaigns with the new facility.

Keywords: nonlinear scaling, uncertainty, dynamic modelling, first principles, simulation, operation of solar PTC plants

1. INTRODUCTION

Modelling and Control of solar thermal power plants is among the research activities performed at Plataforma Solar de Almería (PSA, PSA-CIEMAT). In the past, active developments of mathematical models and control techniques were done with the ACUREX experimental research facility whose key unit was a parabolic trough collector (PTC) field.

The first modelling and control works were made by R. Carmona, Director of PSA center in the period from 1985 to 1987. (Carmona, 1985) defended his dissertation presenting a non-linear distributed mathematical model of the ACUREX field and proposing an adaptive control temperature technique (Camacho et al., 1986). Many control strategies for solar systems have been tested in this facility in its 32 years of life (Camacho et al., 2007; Andrade et al., 2013; L.Brus et al., 2010; Gallego et al., 2013). Nowadays the TCP-100 facility has replaced ACUREX field and it was specially designed to continue the research activities in Automatic Control, aimed at contributing to the enhancement of the efficiency of this plant technology.

Many parabolic trough collector (PTC) plants have been commissioned in the last 20 years. Only in Spain around 45 PTCs power plants have been setup and more than 26 abroad, built or under construction PROTERMOSOLAR (2024). As examples, we can mention the three 50 MW Solnova and the two 50 MW Helioenery parabolic trough plants of Abengoa in Spain, and the SOLANA and Mojave Solar parabolic trough plant constructed in Arizona and California, each of 280 MW power production.

The main approach followed in the research activities developed so far was to define as control objective the regulation of the outlet temperature of the PTC field around a desired setpoint. These are complementary additional objectives dealing with the automatic start-up, different operating point operation changes and shutdowns of the plant. A previous simulation based analysis of the facility used the nonlinear distributed parameter model presented in (Gallego et al., 2016). A more recent system level dynamic model based on the first principles has been developed and presented in (Pérez et al., 2018). This model provides various possibilities for simulation experiments for developing and validating control solutions. In Yebra et al. (2020), these model was used for the development of operation training techniques for the TCP-100 facility.

The nonlinear scaling approach has been earlier used for the ACUREX facility (Juuso and Yebra, 2013; Juuso, 2016). The TCP-100 plant has more detailed control possibilities (Fig. 1). This brings new control cases but also

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makes the tuning more complicated. Simulation models are planned to be used as a replica of the process.

This paper is organized as follows: Section 2 summarizes shortly the TCP-100 plant. Section 3 focuses on different possibilities to use the first principles simulation model in tuning. Section 4 presents the nonlinear data analysis methodology. Section 5 presents a planning of simulation experiments to be performed for typical operation days. Finally, Section 6 provides some concluding remarks and future works.

2. TCP-100 FACILITY

The TCP-100 facility consists of two thermofluid circuits thermally connected by a heat exchanger. This research focuses on the solar field is formed by three PTC loops, each of them composed by two PTCs in a North-South orientation (Fig. 1). Each PTC is 100m length, formed by eight modules and all in parallel. Fig. 2 shows the first PTC in the first loop.

The solar field is in the primary circuit (Fig. 1). In each loop, the PTCs are connected in the South extreme, and *colder* PTC will be always the first in the row, placed at the right part of each loop. Each of the circuits have one tank: the primary tank T-2 with $10m^3$ volume and the storage tank T-1 in the secondary with a volume of 115 m^3. The pumps for each circuit are placed after both tanks and can be controlled. There is an oil cooler in the secondary circuit.

The other loop, including a storage tank, a cooler and the connecting heat exchanger, may be bypassed during the daily operation to let the control system to choose the operational mode at each time. Operating conditions are chosen with different operation modes:

(1) Stopped facility. In this mode, both circuits are in stand-by. Both pumps are stopped and the solar field unfocused.
(2) Both pumps working and solar field unfocused.
(3) The storage tank charging with cooler stopped.
(4) The storage tank charging with cooler working (variable charge).
(5) The storage tank discharging.
(6) Solar field cooling.

The new solar field provides new remarkable features with respect to its predecessor ACUREX. The experimentation of advanced control techniques can utilize new sensors and actuators:

- Inlet and outlet solar field temperature sensors.
- For each loop, inlet and outlet temperatures are measured. Inside the loop, for each PTC: inlet, outlet and middle point temperatures sensors are located.
- Volumetric flow rates for each loop.
- Control valves in each of the loops to regulate mass flow rates in each loop.

3. TCP-100 FACILITY MODEL

The simulation studies can use a hybrid (continuous and discrete) system level model based on the first principles model (Pérez et al., 2018). The parameters for that model

Fig. 1. Top view of the TCP-100 field at Plataforma Solar de Almería (PSA-CIEMAT). The three loops are shown, with two PTCs in each of them, numbered from 1 (rightmost) to 6 (leftmost). The first loop is formed by the connected pair 1-2 (right loop), the second loop by 3-4 (center loop) and the third by 5-6 (left loop).

Fig. 2. Lateral view of the first PTC in the first loop at Pataforma Solar de Almería (PSA-CIEMAT). It is composed of 8 modules of 12 meters length.

were obtained from the plant engineering design project data and are also used in this paper. The system level model has been implemented in the Modelica language with the modelling tool Dymola (DassaultSystems, 2018), which applies special algorithms for the manipulation of hybrid models (Mattsson et al., 1999).

After the symbolic manipulations performed by Dymola, the model can be expressed as a general nonlinear state space system in the form

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \mathbf{u}) \tag{1}$$

$$\mathbf{y} = \mathbf{G}(\mathbf{x}, \mathbf{u}) \tag{2}$$

where $\mathbf{x} \in \mathbf{R}^{28}$, $\mathbf{u} = \{(\mathbf{u_c}, \mathbf{u_d}) \in \mathbf{R}^7 \times \{0, 1\}^3\}$, and $\mathbf{y} \in \mathbf{R}^{N_y}$, where N_y could be arbitrary chosen from the variables computed in the model detailed in (Pérez et al., 2018). The variables are used in two ways:

28 state variables ($\mathbf{x} \in \mathbf{R}^{28}$) .
Each one means a temperature for: each PTC medium control volume (CV, see (Patankar, 1980)), each PTC absorber tube, each PTC glass envelope, each tank medium CV, each tank metal walls, each tank isolation layer, each of both medium CVs in the HEX, the HEX metal wall and the air cooler medium CV. All state

variables are temperatures according to the modelling hypothesis applied.

10 input variables $(\mathbf{u} = \{(\mathbf{u_c}, \mathbf{u_d}) \in \mathbf{R}^7 \times \{0,1\}^3\})$.
Seven real input variables ($\mathbf{u_c} \in \mathbf{R}^7$): solar radiation, ambient temperature, setpoints for both circuits pumps, setpoints for two loops control valves, setpoint for air cooling power; and 3 boolean input variables ($\mathbf{u_d} \in \{0,1\}^3$): bypass activation for the storage tank, for the HEX, and solar field defocusing activation signal.

The Dymola model is capturing the thermal dynamics for the validation of the facility operation modes and operation training purposes as a causal block because of the representation of the inputs and outputs. All the manipulable inputs are shown with the `RealInput` interface component:

- The volumetric flow rates (l/s) in control loops for pumps in primary circuit (Syltherm800 medium) and secondary circuit (Therminol55 medium).
- The setpoint for the air cooler cooling power that modulates forced convection.
- The setpoints for both control valves apertures that vary the mass flow rate (kg/s) through 1st and 2nd loops.
- The Boolean control input to command the bypass of the storage tank (in secondary circuit).
- The boolean control input to bypass the HEX, simultaneously in both circuits: primary and secondary.
- `SF_Defocus` is the boolean control input to defocus the solar field. When this signal is activated the whole solar field is not reached by any solar irradiance.

The non-controllable or disturbance inputs are the solar irradiance and the ambient temperature.

The output of the model is a generic output vector `y[:]` that represents in a general form any arbitrary output computed by the model and that could vary from one to another simulation experiment.

4. NONLINEAR DATA-BASED ANALYSIS

Tests with the previous collector system have shown clear nonlinear behaviour in the normal operating range. The directions of interactions remain constant but the meanings of the variables depend strongly on the operating conditions. In many cases, the nonlinear systems can be implemented with nonlinear scaling and linear interaction models. In the beginning of tuning, the uncertainties need to be taken into account. The representation with natural language is beneficial for understanding an comparing with expert knowledge.

4.1 Nonlinear scaling

The nonlinear scaling was presented as a methodology for improving membership functions of fuzzy set systems already in (Juuso and Leiviskä, 1992; Juuso, 1992). Nonlinear scaling functions (*NSFs*) are monotonously increasing functions $x_j = f(X_j)$ where x_j is the variable and X_j the corresponding scaled variable in the range [-2, 2]. The function $f()$ consist of two second order polynomials, one for the negative values of $X_j \in [-2, 0]$ and one for the positive values $X_j \in [0, 2]$, respectively. Five parameters are needed to define these functions since the overall functions are continuous (Fig. 3). The core area $[(c_l)_j, (c_h)_j]$, corresponding [-1, 1], is within the support area defined by the minimum and maximum values (Juuso, 2004). The corresponding inverse functions $X_j = f^{-1}(x_j)$ based on square root functions are used for scaling to the scaled range.

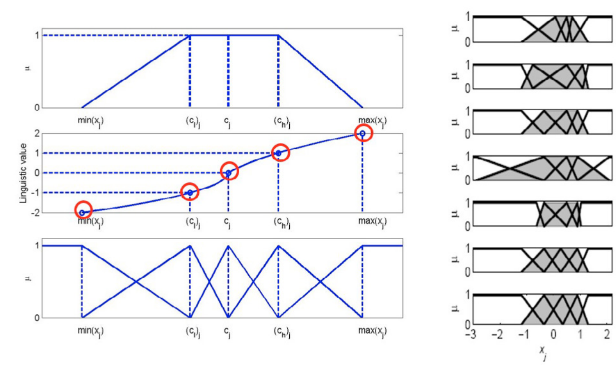

Fig. 3. Nonlinear scaling and membership functions.

Everything can be defined manually, but it is important to obtain the variable specific parameters of the scaling functions by data-based methodologies. Arithmetical means and medians were used in (Juuso, 2004). The current solution uses the central tendency values based on generalised norms (Juuso and Lahdelma, 2010). The analysis divides the measurement values into two parts by the point where the skewness changes from positive to negative, i.e. $\gamma_3^p = 0$. Then the data set is divided into two parts: a lower part and an upper part. The same analysis is done for these two data sets. The estimates of the corner points, $(c_l)_j$ and $(c_h)_j$, are the points where $\gamma_3^p = 0$ for the lower and upper data sets, respectively. Since the search of these points is performed by using the order of the moment, the resulting orders $(p_l)_j$, $(p_0)_j$ and $(p_h)_j$ are good estimates when additional data sets are used. varying operating conditions since the parameters of the scaling functions follow gradually the changes. This helps in detecting the changes even to new situations.

The five corner points are shown in Figure 3. The monotonous increase can be analyzed with differences $\Delta c_j^- = c_j - (c_l)_j$ and $\Delta c_j^+ = (c_h)_j - c_j$. The constraints of the shapes are taken into account by the ratios

$$\alpha_j^- = \frac{(c_l)_j - \min(x_j)}{c_j - (c_l)_j}, \qquad \alpha_j^+ = \frac{\max(x_j) - (c_h)_j}{(c_h)_j - c_j}, \tag{3}$$

where c_j is the central tendency value, corresponding 0. The scaling functions are monotonous and increasing if these ratios are both in the range $[\frac{1}{3}, 3]$, see (Juuso, 2009). In genetic tuning, the shape requirements are taken into account. These constraints of the shape parameters are clear also for the manual tuning for achieving monotonously increasing functions. The scaling functions may contain linear parts if some coefficients α_j^- or α_j^+ equals to one. In fully linear case, these coefficients are both one and the distances $(c_l)_j - \min(x_j)$ and $\max(x_j) - (c_h)_j$ equal.

4.2 Uncertainty processing and natural language

Monotonously increasing nonlinear scaling functions, $x_j = f(X_j)$ and $X_j = f^{-1}(x_j)$, are suitable for inductive mappings in the extension principle. This can be used in transforming fuzzy numbers and membership functions to both directions between the real and scaled values.

A set of membership functions (*MFs*) can be generated by selecting the locations for the functions (Fig. 4). Natural language interpretation provides a basis for the transformation. The integer numbers {-2, -1, 0, 1, 2} correspond labels {very low, low, normal, high, very high} or {high negative, negative, zero, positive, high positive} or {accelerating decrease, decrease, constant, increase, accelerating increase}. The vocabulary can also be chosen in a different way, e.g. by using modifiers highly, fairly, quite (Juuso, 2012). Only the sequence of the labels is important.

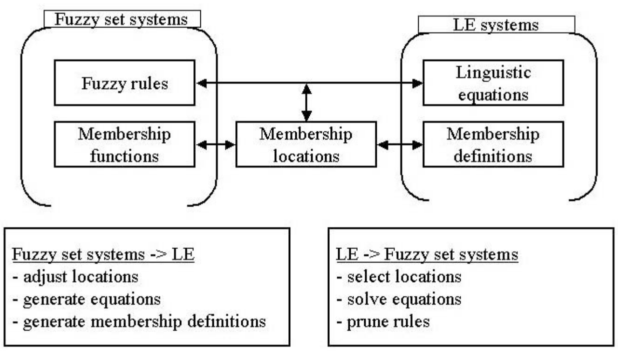

Fig. 4. Fuzzy set systems and linguistic equations (Juuso, 2004).

The set of *MFs* depends strongly on the shape of the *NSFs* as can be seen in the examples shown in Figure 3. The number of *MFs* is not limited to five. Modifiers of the labels can introduce domain expertise for defining corresponding membership locations in the scaled range (Fig. 4).

The scaling can be extended to the temporal analysis: increasing and decreasing changes can be quantified, trend and fluctuation indices are calculated by using scaled values. Resulting values are within the range [-2, 2] and can be interpreted with *MFs* as in Figure 3 and explained with natural language.

Uncertainties are embedded in the nonlinear scaling approach: feasible ranges and labels are presented with *MFs* (Fig. 3). The data-based computation of the *NSFs* is done by using equal-sized sub-blocks, i.e. the norm for several samples can be obtained as the norm for the norms of individual samples (Juuso and Lahdelma, 2010; Lahdelma and Juuso, 2011). The parameters can have differences between the sub-blocks, which introduces uncertainties to the *NSFs* and *MFs*.

The nonlinear scaling can be used for any time periods. The scaling functions from short time periods provide useful information for detecting changes in operating conditions.

The representation with natural language demonstrates how well the experiments cover the operating areas.

5. PLANNING OF EXPERIMENTS

The TCP-100 solar thermal power plant replaces the ACUREX experimental research facility. Therefore, the scaling functions of the irradiation (W/m^2) do not change which means that also the indicator of the cloudiness remains the same. This is a good starting point for the planning of the experiments. All the other variables are in totally different value ranges.

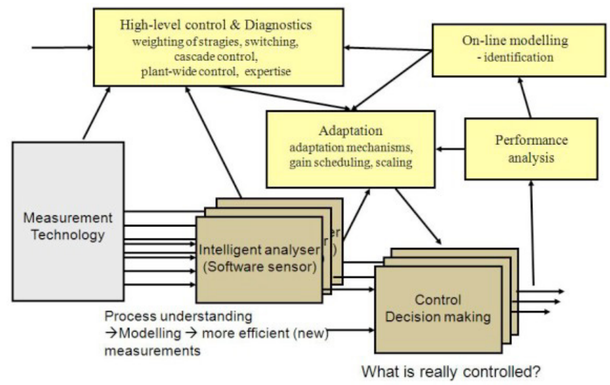

Fig. 5. Intelligent analyzers and control.

5.1 LE systems

In the linguistic equation (LE) systems, all variables x_j are handled with the nonlinear scaling functions: $x_j = f(X_j)$ and $X_j = f^{-1}(x_j)$, see Section 4. The interactions of the scaled values X_j are presented with linear equations. Each feedback controller is a PI-type LE controller with one manipulating variable, oil flow, and one controlled variable, the maximum outlet temperatures of the loops. The PI-type means that the change of control is the sum of the error and the change of error, all in scale [-2, 2]. The acronym LE means that dimensionless scaled values are used in the control equation.

The very compact basic LE controller provides a good basis for advanced extensions: both scaling functions and control equations can depend on operating conditions. All different types of PID controllers can be used as the linear structure of the interactions.

Intelligent analysers are LE systems which 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 analysis of previous test campaigns has introduced many improvements, which will be used in the new TCP-100 facility. In the first step, the current interaction algorithms are utilized:

- The working point is obtained from the effective irradiation and the difference between the outlet and the inlet temperatures. The effect of the ambient temperature will be tested.
- Asymmetry detection improves operation.
- Fluctuation indicators for detecting cloudiness and oscillations improve stability.
- LE based indicators of the fast changes of the temperatures (inlet, outlet and difference).

5.2 Adaptation

Adaptive LE control uses correction factors that 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. These are for later studies.

Model-based control limits the acceptable range of the temperature setpoint by using the chosen working point. The fluctuation indicators are used for modifying these limits to react better to cloudiness and other disturbances. The manual setpoints are used only within these limits. Dynamic models developed for the TCP-100 facility could be used for development in this task.

High-level control is aimed for manual activating, weighting and closing different actions. As there are many actions, this is needed to run the tests efficiently.

The controller contains several parametric scaling functions for variables, errors, changes and corrections. Since there is no actual test data available from the new research plant, the parameters are tuned before the test campaign by using previous test results from the ACUREX plant and adjust them to correspond better to the specifications of the new TCP-100 collector field or using the simulator of the new field.

5.3 Simulation experiments

The full first principles model is highly complicated and a lot of tuning work is needed before it can be used in tuning the controller for the special cases listed above. Actually, the simulator would already need adaptive parts. A better way is to focus first on the modules of the PTC loops (Fig. 2). There are three sequential loops in the solar field (Fig. 1) which all consist of two PTCs both having eight similar modules.

All the modules can be handled with the same parametric LE model. The models are tuned to different operating areas since they are working in different operating conditions: the input and output temperatures depend on the sequence of the modules and loops. Additional differences between the loops are introduced by the control. The development of these submodels has been started in simulation study. The corresponding parts of the first principles model can be used together with the LE model.

The project will continue first with the full dynamic models enhanced with the new LE models. Then the full set of the experiments can be started in the real new TCP-100 facility which finally provides the data which can be used in the tuning of the plant and the control system.

5.4 Test campaigns

The simulation studies provide a starting point for the test campaigns with the new field. The parameters will be updated offline during the test days by using the recursive approach.

The TCP-100 facility includes more units, loops and connections. There are more sensors for the temperatures and volumetric flows. The control is available in each of the loops. The dynamic simulation model includes 28 state variables and seven input variables (Section 3).

The dynamic simulation model will be used as a plant in the planning of the test campaigns. This is a flexible solution to analysing different weather conditions and disturbances. The strongly fluctuating situations are difficult to handle reliably with models. However, they can be taken as scenarios in this model based analysis. The idea of the nonlinear scaling is that the algorithms of the interactions remain unchanged.

6. CONCLUSIONS AND FUTURE RESEARCH

This research focuses on starting to apply the intelligent analysers, models and control algorithms for the new TCP-100 solar thermal plant. The scaling functions of the ACUREX facility remain unchanged for the irradiation which also means that the earlier indicators of the cloudiness. More units, loops and connections are included in the new facility. The algorithms are not changed and the data analysis can be done by using the dynamic models for a limited set of measurements and subsystems.

This paper presents the methodologies for the simulation experiments with single modules, PTCs and loops. Three loops form the field. These adaptive parts are needed in the first principles models before going to the full simulation experiments. The work can be started with the loops and modules by using parametric linguistic equation models. The simulation studies will be extended with these models before going to the test campaigns with the new TCP-100 facility.

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