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A combinatorial optimization problem to control a solar reactor

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Abstract

In the scope of the HYDROSOL project and the consecutive HYDROSOL-2 project, both funded by the EC, a pilot plant was installed in the SSPS solar tower at CIEMAT–Plataforma Solar de Almería (PSA), Spain, for producing solar hydrogen from water using a ferrite-based redox technology. It consists of two reactors where hydrogen and oxygen production cycles are alternated for quasi-continuous hydrogen production. In the first step (water splitting), an exothermic reaction takes place at an operating temperature of 800 ºC. The second step (thermal reduction) is an endothermic reaction which requires an operating temperature of 1200 ºC.

The HYDROSOL-3D project focuses on the next step towards commercialisation, carrying out all the activities necessary to prepare the erection of a 1 MW solar demonstration plant. HYDROSOL-3D concerns, for example, the implementation of the control strategies and algorithms in a specific process control system for the plant. This paper summarises the work carried out by CIEMAT-PSA to develop a control strategy using a dynamic model of a solar hydrogen production plant which was developed based on previous experiments with this pilot plant. This model includes both a solar field and a processing plant and is able to simulate the concentrated solar power received by the reactors and the thermal and chemical reactor behaviour. Particular attention is given to the control strategy for controlling the operating temperatures in the solar hydrogen reactor, considering a new algorithm to choose the heliostats which must be focused.

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1. Introduction

A huge number of processes which require high temperatures could be carried out using concentrating solar thermal systems such as central receiver solar thermal plants. These solar power towers use optical devices and sun tracking systems to concentrate solar irradiance into a receiver. One operating problem is the heliostat control

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strategy to obtain a desired temperature and flux distribution in the receiver [1]. With the aim of avoiding material degradation in the receiver, some control strategies have been published. Artificial vision systems using CCD cameras were used in [2] to maintain the temperature distribution on the receiver surface as uniform as possible, and to handle offset correction [3]. [4] proposes an optimized aiming point strategy using a solar field model, called HFCAL, and an improved TABU algorithm to find a proper distribution of heliostats.

The second operating problem with regard to the control of heliostats is the fact that, in some occasions, it is critical to maintain a desired temperature in the receiver. This is the case of the Hydrosol-2 pilot plant installed in the SSPS solar tower at the CIEMAT–Plataforma Solar de Almería (PSA), Spain [5]. In this solar hydrogen production plant, temperature in the reactor should be precisely switched and maintained in two particular values. In [6] an adaptive controller was tested obtaining promising results. In that case, the focusing strategy to choose the heliostats is based on a model of the solar field. The first-focused heliostats are those with the lower thermal power contribution.

In this paper, a controller based on [6] is proposed. In this case, the model of the solar field is used to obtain an array such as each element is the thermal power contribution of each heliostat. On the other hand, an inverted model of the process is used to predict the thermal power required to reach the desired temperature. Therefore, the problem is similar to the Knapsack problem [9], due to a suitable combination of elements must be found to fulfill a required quantity. The Knapsack problem appears in several applications such as smart-grids management [7,8], financial models, manufacture and production planning [9].

The present paper is organized as follows: Section 2 gives an overview of the plant. Section 3 describes the proposed controller and a simulation result is reported and discussed in Section 4. Finally, some conclusions are outlined in Section 5.

Nomenclature

K_p	proportional gain (ºC^{-1})
n	number of heliostats in the solar field
n^θ	number of available heliostats
$\mathbf{Nh}$	array of focused heliostats
Nh_Σ	number of focused heliostats
$\mathbf{Nh_{FF}}$	array of focused heliostats given by the feedforward controller
$Nh_{\mathbf{FF}\Sigma}$	number of focused heliostats given by the feedforward controller
I	direct irradiance (W/m^2)
P^*	concentrated power setpoint (W)
P_1^*	ideal concentrated power setpoint (W)
P_2^*	discretized ideal concentrated power setpoint (W)
$\hat{\mathbf{P}}$	array of estimated concentrated power contributions (W)
$\hat{\boldsymbol{P}}^\theta$	array of estimated concentrated power contributions of available heliostats (W)
$\hat{p}_i$	estimation of the concentrated power with the i-heliostat (W)
t_m	time in which a maximum (regeneration cycle) or minimum (generation cycle) occurs in the concentrated power (s)
t_{sw}	time in which the thermochemical cycle is switched (s)
T	mean temperature in the reactor (ºC)
T^*	temperature setpoint (ºC)
T_i	integral time (s)
T_0^*	square-wave temperature setpoint (ºC)
T_s	PI sample time (s)
T_{sFF}	feedforward sample time (s)

T_1^*	ideal temperature setpoint (ºC)
ΔNh	number of heliostats that must be focused (positive values) or taken out of focus (negative values)
ΔP^*	power difference required between two feedforward actions

2. The Hydrosol facility

The Hydrosol facility [5] is a 100 kW pilot plant for solar hydrogen production from water that is located on the SSPS-CRS tower at the PSA. The hydrogen production process is the water splitting by a two-step thermochemical cycle using ferrites as catalyst. The cycle consists of two reactions, the hydrolysis capturing the oxygen from the water at the surface of the catalyst and the regeneration of the catalyst releasing the captured oxygen.

The pilot plant has a nitrogen feed system, a boiler, several heaters, two reactors and an exhaust gas analysis system. Using two reactors it is possible to run both steps of the cycle in parallel. Inside each chamber are individually placed nine pieces of square-shaped monolithic honeycomb absorbers made of siliconized silicon carbide (SiSiC). These honeycomb absorbers are coated by a thin film of ferrite that acts like catalyst. Into the center of each honeycomb structure a thermocouple has been inserted to monitor the temperature. The solar flux is measured with a Lambertian white moving bar system.

The feeding gas is introduced through channels in the outer part of each chamber while exhaust gases and products are collected in one center pipe attached to the rear part of the housing. To confine the reaction, each module is equipped with a quartz window fixed by a water-cooled window frame.

The heliostat field of SSPS-CRS Solar facility has 93 heliostats and is able to provide about 1.5 MWth. For powering the two modules of the reactor with different solar flux the heliostat field is divided into different parts and to actuate and control those separately.

During the splitting process, steam is fed in the module where hydrolysis reaction is taking place at 800°C, while, at the same time, in the other chamber the catalyst is regenerated at 1200°C. Nitrogen is fed into both chambers, since it works as the carrier gas and also to ensure an inert atmosphere inside the chambers. Cycles usually takes 20-30 minutes. After this time, the mode of operation in each module is switched.

3. Temperature control

As previously commented, the redox reactions take place at two temperature levels (800ºC for generation and 1200ºC for regeneration). The aim of the proposed controlled in this paper is to reach and maintain these two references in a low switching time.

This controller is shown in Fig.1 for the case of a single reactor. A signal generator calculates an appropriate reference for the temperature, T^*, and concentrated power, P^*, in one reactor. A feedforward block is in charge of calculating which heliostats must be focused using a model of the solar field and a combinatorial algorithm which solve a Knapsack problem. The output is an array, $\boldsymbol{Nh_{FF}}$, which includes information of the heliostats that must be focused:

$$Nh_{FF}(i) = \begin{cases} 1\ if\ the\ i-heliostat\ must\ be\ focused, \\ 0\ otherwise \end{cases} \quad i = 1 \ldots n$$

Due to model mismatches, the feedforward control is combined with a feedback controller, a PI, which adds or takes out of focus heliostats, depending on the error between the setpoint temperature and the real one. The output, ΔNh, is an integer value which indicates how many heliostats must be focused (positive values) or taken out of focus (negative values).

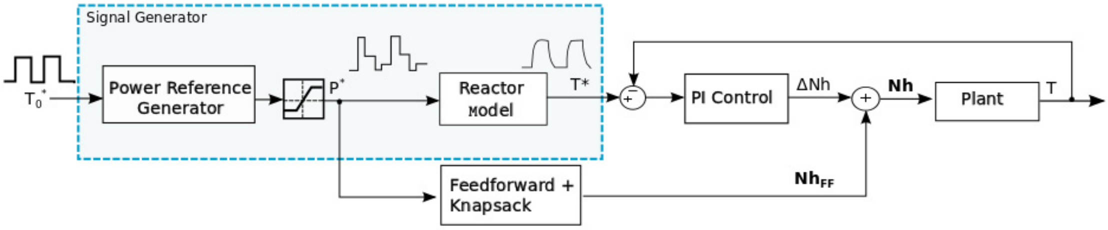

Fig. 1.Controller scheme.

3.1. Signal generator

Since the hydrogen production operation is a cycling process, two consecutive temperatures must be reached in the reactor following the process described in section 2. The ideal temperature setpoint would be a square wave, *To**, between 800 and 1200ºC, with a period of one hour. Nevertheless, in a real process, it is not feasible to switch between these two temperatures immediately, due to the thermal inertia of the process, delays related with the focusing system and constraints in the materials to avoid suffering from thermal stress.

In order to obtain a more realistic signal reference, taking into account a maximum temperature gradient but reducing the switching time, a signal generator is proposed.

Firstly, a power generator calculates the ideal temperature reference, T_1*, as a first-order response using *To** as input:

$$\tau \dot{T_1}^* + T_1^* = T_o^*,$$

where the constant time, τ, can be tuned to reduce the switching time, but also it should be limited to avoid breaching the constraint of the temperature gradient.

The ideal temperature, T_1*, is used to estimate the solar concentrated power, P_1*, needed to reach such desired temperature. For this step, the model described in [10] was inverted, exchanging *P* for *T* as input of the model. To calculate the derivative of the reactor temperature, an approximated derivative block was used. In the case of using a measured signal as input instead of an ideal one, this block should be connected to a low-pass filter in order to reject the noise in the signal, otherwise this noise will be increased by the derivative. Since the model was developed using the a-causal Modelica modeling language, no additional changes were required in the inverted model.

Due to the solar field is a discrete system and continually moving the heliostats is not a feasible goal, the objective is to transform the power reference in order to reach two different levels in each cycle. Therefore, a new signal, P_2*, is calculated:

$$P_2^*(t) = \begin{cases} P_1^*(t_{m1}) & if \quad 0 < t \le t_{m1}, \\ P_1^*(t_{sw1}) & if \quad t_{m1} < t \le t_{sw1}\ , \\ P_1^*(t_{m2}) & if \quad t_{sw1} < t \le t_{m2}, \\ P_1^*(t_{sw2}) & if \quad t_{m2} < t \le t_{sw2}\ , \\ P_1^*(t_{m3}) & if \quad t_{sw2} < t \le t_{m3}, \\ & \quad \dots \end{cases}$$

where t_{sw1}, t_{sw2},.., are the times when the thermochemical cycle switches in the reactor and t_{m1}, t_{m2},.., are the times when a maximum or minimum occurs in P_1^*:

$$P_1^*(t_{m1}) = \max P_1^*(t) \ / \ 0 < t \le t_{sw1}\ , i = 1,$$
$$P_1^*(t_{mi}) = \max P_1^*(t) \ / \ t_{m(i-1)} < t \le t_{swi}\ , i > 1.$$

Since the input of the model is an ideal temperature signal, the output of this inverted model may achieve values out of the real range. Therefore, a saturation block is included to limit the power between 0 and the maximum obtained with the whole field focusing on the target. The result is the power reference, P^*, which is also used to estimate the final temperature reference, T^*, using the model explained in [1].

$$P^*(t) = \begin{cases} P_2^*(t) & if \quad \hat{P}_{min}(t) \leq P_2^*(t) \leq \hat{P}_{max}(t) \\ \hat{P}_{min}(t) & if \quad P_2^*(t) < \hat{P}_{min}(t) \\ \hat{P}_{max}(t) & if \quad P_2^*(t) > \hat{P}_{max}(t) \end{cases}$$

Fig.2 shows an example of the signal generator. Ideally, the temperature in the reactor should follow the initial signal, T_o^*, which is converted into a first-order signal, T_1^*. The solar power required to reach this temperature, P_1^*, obtained with the inverted model, is used to define the power levels which occur at times t_{m1}, t_{m2}..., and generate the reference P_2^*. After the saturation, the final power and temperature references are P^* and T^*.

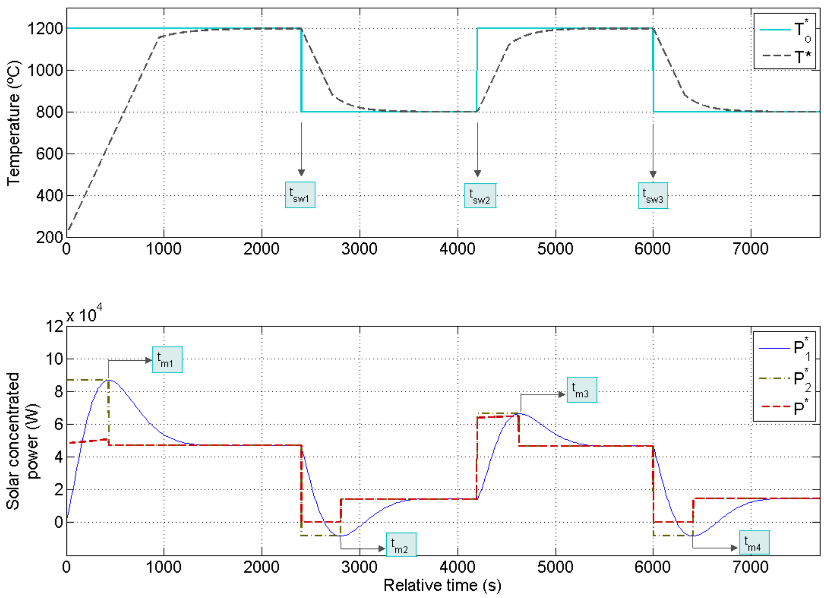

Fig. 2. Results of the signal generator.

3.2. Feedforward controller

The feedforward control tries to eliminate the effects of the disturbances before they produce changes in the controlled variable [11] using a mathematical model of the process. In this case, the model of the solar field described in [10] is included to predict the power contribution of each heliostat. Using the time, date and irradiance at each sample time (see Fig. 3), the solar field model calculates the concentrated power of each heliostat assuming the whole field is focusing the target.

$$\hat{\boldsymbol{P}} = \{\hat{p}_1, \hat{p}_2, \dots, \hat{p}_n\}$$

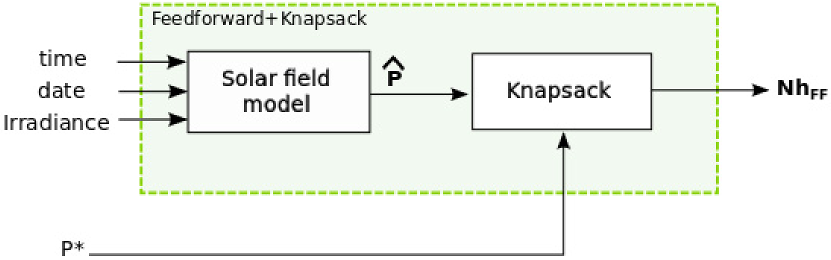

Fig. 3.Feedforward and Knapsack scheme.

This process is repeated at times $\{t_{m1}, t_{sw1}, t_{m2}, t_{sw2}, \ldots\}$. If T_{mFF} is defined as the time interval between two events, at sample time t, the model makes an estimation, $\widehat{\boldsymbol{P}}$, along the prediction horizon T_{mFF} assuming that irradiance disturbances remain constant, $I(t+T_{mFF}) \approx I(t)$.

Once the array of power contributions is calculated at each sample time, the next step is to decide which heliostats are going to be focused to achieve the desired power, P^*. The aim is to focus the best combination of heliostats that fulfill the power requirements. It is a combinatorial problem commonly known as Knapsack problem.

3.3. The Knapsack problem

The Knapsack problem is formulated to achieve a specified value by selecting among different possible items. In general, it can be formulated such as:

$$\begin{gathered} maximize \sum_{j=1}^{n} s_j x_j \\ subject\ to \sum_{j=1}^{n} r_j x_j \leq b\,, \\ x_j \in \{0,1\}\,,\ j = 1..n, \end{gathered}$$

where $s \in \mathbb{R}_+^n$ is a weight vector with positive components s_j, x_j=1 means that the item j is selected, r_j is the weight of the item j and b is a real constant.

This problem can be particularized to obtain the combination of heliostats that must be focused in a central receiver system:

$$\begin{gathered} maximize \sum_{j=1}^{n} \hat{p}_j x_j \\ subject\ to \textstyle\sum_{j=1}^{n} \hat{p}_j x_j \leq P^*\,, \\ x_j \in \{0,1\}\,, \qquad j = 1..n \end{gathered} \tag{1}$$

The array of focused heliostats will be:

$$\boldsymbol{Nh_{FF}} = \{x_1, x_2, \ldots, x_n\}$$

Numerous algorithms have been proposed to tackle this problem [12]. In this paper, the MATLAB® function *ce_knapsack.m* which applies the algorithm proposed in [13] is used.

An example of the evolution of the algorithm is depicted in Table 1, being S the optimal solution in each iteration, the maximum number of iterations is 100 and the algorithm is stopped if the optimal solution is repeated in 10 consecutive iterations. For this example, the objective value chosen is P^*=14300 W and the estimated power array is: $\widehat{\boldsymbol{P}}$={2049, 2022, 2034, 1919, 2050, 1974, 2005, 2043, 2057, 1892, 2063, 1987, 2083, 2082, 1969, 2077, 2003, 1880, 2097, 2094, 1985, 1851, 2101, 2091, 2018, 1897, 2111, 2108, 2002, 1869}. The distribution of these values in the solar field is shown in Fig.4 where the receiver is located at 26.45 m height, 0.9 m East and 0 m North. In this example I=665.9 W/m^2, date=24/02/2011 and time=09:51:00.

At the end of the simulation, the optimal value found is quite close to the desired one, S= 14299,56 W, being the $\boldsymbol{Nh_{FF}}$ array the following one: $\boldsymbol{Nh_{FF}}$ = {0, 1, 1, 0, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0}. In Fig. 4, the values in red correspond to those heliostats that must be focused on the receiver.

Table 1. An example of the algorithm to solve the Knapsack problem.

Iteration number	S=$\sum_{j=1}^{n} \hat{p}_j x_j$
1	14224.41
2	14296.52
3	14298.19
…	…
100	14299.56

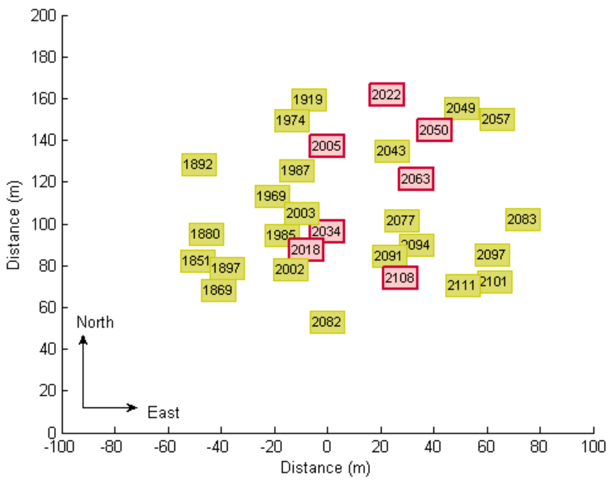

Fig. 4. An example of each heliostat power contribution (W) estimated with the model explained in [1] .

Commonly, when the controller is switched on, the solar field is out of focus, and the Knapsack problem is the one defined by (1). Nevertheless, in the following feedforward actions, the optimal solution may be, for example, to change completely all the focused heliostats. With the aim of reducing the number of movements in the heliostats, the problem is reformulated as:

$$maximize \sum_{j=1}^{n^\theta} \hat{p}_j^\theta x_j$$

$$subject\ to \sum_{j=1}^{n^\theta} \hat{p}_j^\theta x_j \leq |\Delta P^*|$$

$$x_j \in \{0,1\}, \qquad j = 1..n^\theta$$

where $\Delta P^*=P^*-P$ and

$$n^\theta = \begin{cases} n - Nh_\Sigma & if\ \Delta P^* > 0 \\ Nh_\Sigma & if\ \Delta P^* < 0 \end{cases}$$

$$\widehat{\boldsymbol{P}}^\theta = \begin{cases} \{\hat{p}_j\} & \forall j\ /\ x_j = 0\ if\ \Delta P^* > 0 \\ \{\hat{p}_j\} & \forall j\ /\ x_j = 1\ if\ \Delta P^* < 0 \end{cases}$$

3.4. Feedback controller

Since the feedforward controller is activated only when a change in P_2* is detected (at times t=t_{m1}, t_{m2},.., t_{sw1}, t_{sw2},..), the solar concentrated power between two sample times vary from the one predicted due to changes in irradiance and sun position. In addition, the output of the feedforward might be far from the optimal one due to model mismatches.

Due to these errors, this feedforward controller is combined with a feedback controller. In this case a PI controller is used to add or take out of focus heliostats depending on the difference between the temperature setpoint and the real one. The output of this PI, ΔNh, is an integer value so that positive values mean the number of heliostats that must be focused and negative ones the number of heliostats which must be taken out of focus.

4. Simulation results

Fig. 5 shows a simulation of the proposed controller using as real plant the model described in [10] but including an error of 20ºC in the model of the reactor and 5 kW in the model of the solar field. The parameters of the PI are Kp=0.02 ºC-1, Ti=510 s and Ts=120 s. As can be observed, the mean temperature in the reactor, T, follows quite well the changes in the setpoint, T*. At the beginning, since the slope of the reference is lower than the one obtained, the control signal of the PI, ΔNh, is decreasing. At t=432 s the feedforward is activated and the array of heliostasts is modified. Then, the reference is maintained due to the changes in the PI control signal. At time t=2400 s, the reactor changes from regeneration to generation, the feedforward gives a new NhFF and just two heliostats are maintained. The feedforward is activated again at t=2808 and the PI only adds one heliostat more. The thermochemical cycle is repeated at t=4200 s.

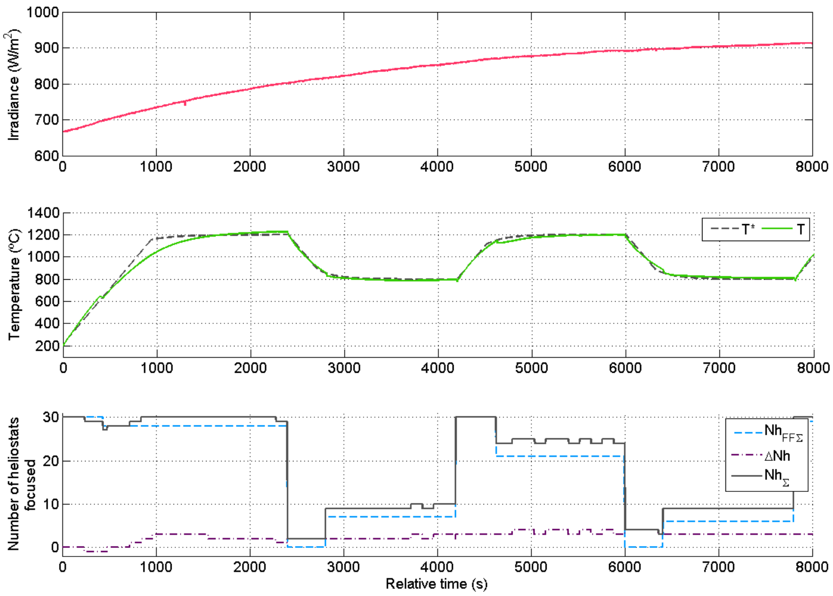

Fig. 5. Simulation results with an error mismatch of 20ºC in the reactor model and 5kW in the solar field model.

5. Conclusions

The Hydrosol project has demonstrated that it is possible to produce hydrogen from water using a ferrite-based redox technology. This paper presents a heliostat control strategy to operate this prototype plant while maintaining the two required temperature levels. Although the main feedback controller is a classical one, a novel procedure to choose the focused heliostats is proposed. A feedforward action based on a validated model is combined with a combinatorial algorithm to solve a typical Knapsack problem. Simulation results show that it is possible to obtain satisfactory behaviors without losing robustness. Future papers will include results of the controller tested in the real plant.

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