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DESIGN A GAIN SCHEDULED FUZZY CONTROLLER FOR DISTRIBUTED PARABOLIC SOLAR COLLECTORS

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Abstract: The subject of this article is the gain scheduled fuzzy control for the field of distributed parabolic solar collectors. System modeling has been done in different operation points. These different operation points are caused by various conditions occured by the nonlinear and time-varying behavior of the system based on the different operating points that are considered due to the presence of various disturbances and inputs, the switching mechanism between controllers is performed by a time-controlled structure, which will reduce the effects of disturbances on the system response. The PID controller is then designed based on the Anti-Windup circuit and a feedforward controller that runs parallel to it. The use of a feedforward controller can also improve the system response time and its overshoot value, as well as reduce the effect of disturbances on the system.
Keywords: parabolic solar collectors, fuzzy controller

1. INTRODUCTION

In this paper, the collectors of the distributed parabolic solar field and its control using gain scheduled fuzzy controller are studied. The distributed solar collectors field consists of parabolic-shaped planes with tubes in the center through which fluid flows. The goal is to bring the temperature of the fluid leaving the pipes to the desired temperature and its temperature resistance to turbulence is due to environmental changes. The control parameter to achieve this is the fluid flow inside the pipes which is controlled by the installed pumps. In general, it can be said that most industrial processes, such as the system in question, are nonlinear, which leads to different work points for different situations. However, classic controllers such as PID are designed for a fixed operating point range and has constant parameters and this results in controllers to perform poorly for nonlinear operating areas. For this reason, we try to approximate the nonlinear behavior of the system by considering different points of work with linear behavior. The presence of a supervisory fuzzy switch will make it possible for any work point due to the conditions imposed on the system, a suitable controller specific to that work point and condition can be selected. Classic linear controllers have been designed for different work points, and one of them will be selected with the presence of fuzzy switches in different working conditions. But despite setting different work boundaries and switching between them, again, the presence of turbulence in the same range can have adverse effects on the system response. For this reason, the forward controller is also used to reduce the effect of rapid and effective disturbances entering the system within a certain operating range. Paralleling the forward controller with the PID controller makes the system more robust against changes in the temperature of the fluid entering the pipes and changes in the intensity of solar radiation and the environment in which the disturbances enter the system [1]. It is important to note that using a PID controller with a normal structure allows the control signal to be saturated. However, its saturation will lead to the saturation of the operator and this can disrupt system performance. For this reason, a PID controller designed based on the Anti-Windup circuit is used. In the continuation of this article and in the second part, the field of parabolic solar collectors and the relations governing it are discussed. The third section deals with how to design a fuzzy observer controller and in the fourth part, to model the field of parabolic solar collectors in a three-part method, In the fifth section, we design a PID controller that runs parallel to the forward controller. The results are examined and its comparison with other modes is discussed.

2. DESIGN OF CONTROLLER

— Parabolic solar collectro field

Defining an accurate model for the system is essential for the control problem of the distributed parabolic solar field, and it needs an appropriate system identification method. In the system identification methods, describing a system is highly dependent on prior knowledge about the system. In addition to the physical description, using signal bases methods are common as described in [2-3] for the space application, in [4-5] tracking systems and [6-7] in the shared control frameworks. Meanwhile, in the identification process, the measured parameters by sensors must be transmitted in real-time mode. The compressed sensing methods are usually used to decrease the required bandwidth in the communication link. The time for generating compressed data for transmission is an essential key when we consider mobile devices, with the fact that data should be sent to the central processor as soon as possible. In addition, there are some wearable sensors that have a limited amount of power, and may only be capable of doing simple computations. With the aim of increasing the speed and simplicity of the compressors, [8] proposes an approach that can generate compressed ECG samples in a linear method and with CR 75%. In structural health monitoring/identification (SHMI), sensors intermittently monitor the operational condition of the system and send the recorded data to a remote server for processing. Data compression can be used to decrease the required storage size of the received data, and for efficient use of transmission link bandwidth, because of the enormous volumes of sensor data produced from the sensors. In [9-10-11], the fundamentals for acquiring the data for the control purposes are presented. In this paper, it is supposed that the extracted model is based on the combination of model-based and signal-based methods. The distributed parabolic solar collectors field found here are taken from a real specimen in Almeria, located in Tabarnasa, southern Spain, Because its function is well described in the references [12]. This field consists of 480 distributed solar collectors in 20 rows consisting of 10 parallel rings and each ring is 172 meters long [13],[14]. According to the figure 1, each collector consists parabolic mirrors in order to focus the sun's rays on the receiving tubes. Oil is pumped into the tubes at the center of the parabolic plates. The temperature of the oil pumped from the storage tank into the pipes is indicated by T_{in}, which has a lower temperature than the desired temperature at the outlet. The circulation of oil inside the pipes causes it to heat up, which eventually the heated oil enters the storage tank.

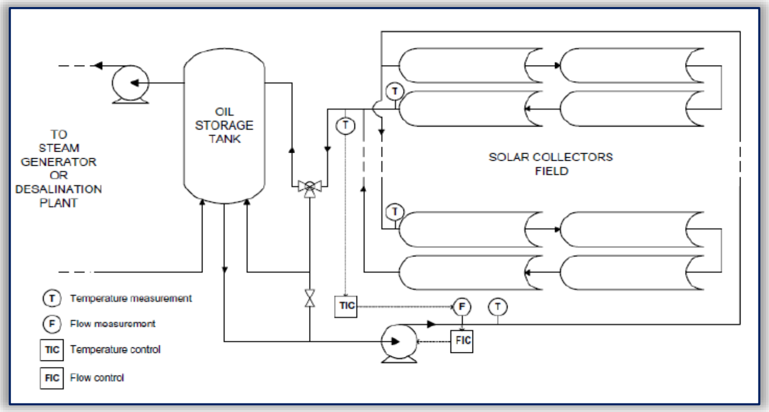

Figure 1. Distributed parabolic of solar collectors field diagram

The dynamics of the field of parabolic solar collectors can be expressed by the relations (1) and (2) in which the temperature of the oil released from the pipe is determined by the factors affecting it [15].

$$\rho_m C_m A_m \frac{\partial T}{\partial t}(t,x) = \eta_0 GI(t) - p_{rc} - D_i \pi H_t (T_m(t,x) - T_f(t,x)) \qquad (1)$$

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t}(t,x) + \rho_f C_f q(t) \frac{\partial T_f}{\partial t}(t,x) = D_i \pi H_t (T_m(t,x) - T_f(t,x)) \qquad (2)$$

In the above equations, the index m represents the metal parameters and the index f represents the fluid parameters and represents the sum of the radiation and the lost conduction temperature, which is usually modeled by a linear $H_t(T_m(t,x) - T_a(t))$ relation. Another energy equilibrium equation can be used to analyze the dynamics of the distributed parabolic of solar collectors. Many authors have used equation (3) to analyze the dynamics of the field of parabolic solar collectors [16].

$$A\frac{\partial T}{\partial t}(t,x) + q(t)\frac{\partial T}{\partial t}(t,x) = \frac{\eta_0 G}{\rho C} I(t) \qquad (3)$$

In the above equations, ρ is the density of oil, C is the specific heat capacity, A is the transmission area, T is the temperature, T_a is the ambient temperature, η_0 is the Optical efficiency of mirrors, G is the collector opening, I is the intensity of the sun's rays, D_i is the inner diameter of the tube, D_o is the outer diameter of the pipe, H_t is the thermal transfer coefficient between oil and metal, q is the oil flow rate.

In the equations above, $T(x,t)$ states how much fluid temperature inside the tubes is at position x and time t. The boundary condition for the above equations is defined as $T(t,0) = T_{in}(t)$, in which T_{in} is the temperature of the fluid entering the pipes and it is known as one of the disturbances to the system. The main purpose of the solar collectors field is to control the oil temperature out of the pipes and display it as $T_{out}(\mathrm{t}) = T_{in}(t,l)$.

— Fuzzy observer controller

Using fuzzy logic, it is possible to have a structure that monitors the controllers so that the supervising controller can adapt the system to the conditions in which it is located [17],[18],[19]. In fact, in order to have Gain Scheduled Fuzzy Controller, for the field of parabolic solar collectors, the fuzzy keying pattern can be used in such a way that the controller related to that point can choose the work point for the different conditions in which the system is placed [20]. Disturbances in the field of distributed solar collectors including, the temperature of the oil entering the pipes and I_{rad}, intensity of solar radiation. Because the system is nonlinear and time-varying, suitable operating ranges are considered for the system for different disturbances and around each work point, a linear model for the system is approximated. Models are displayed with M_i, which is the index of the corresponding model number. Now for each model, a suitable controller must be designed, which is indicated by C_i.

Now a fuzzy observer key structure should be designed to select a controller for each of the disturbances. By considering T_{in} and I_{rad} as fuzzy inputs, the observer control structure can be displayed as shown in Figure 2. The range of changes for the temperature of the oil entering the pipes and also for the intensity of solar radiation is as follows:

≡ $T_{in} = [100^0 C, 200^0 C]$

≡ $I_{rad} = [200 \frac{W}{m^2}, 1000 \frac{W}{m^2}]$

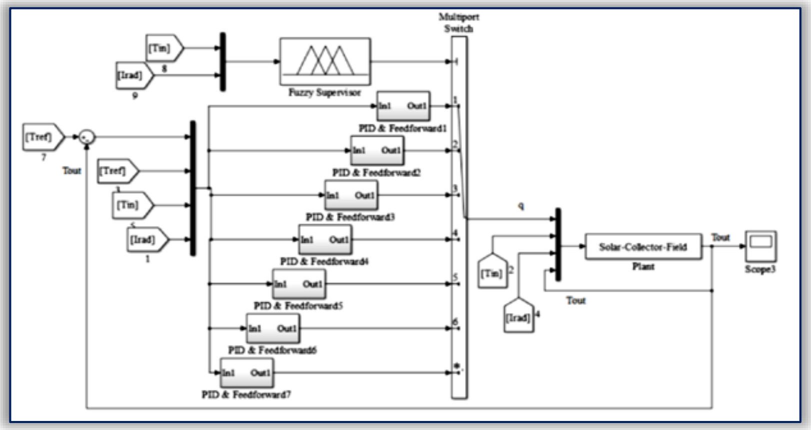

Figure 2. Supervisor control structure by fuzzy switch

Fuzzy variables are now considered for both named variables.

$$\mathrm{ST} = \{T_{in}, \mu_I(T_{in}) | T_{in} \in T\}$$

$$\mathrm{SI} = \{I_{rad}, \mu_I(I_{rad}) | I_{rad} \in I\}$$

Five language phrases are defined for each fuzzy variable: {VerySmall, Small, Normal, Large, VeryLarge}

The membership functions are in the form of triangles with the centers shown in Figures 3 and 4. According to Table 1, which includes fuzzy rules, it is possible to determine which controllers to choose for different disturbances.

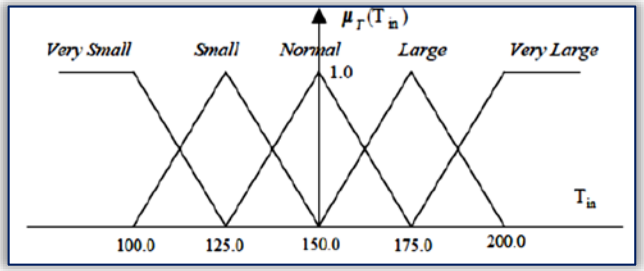

Figure 3. Fluid input temperature membership function

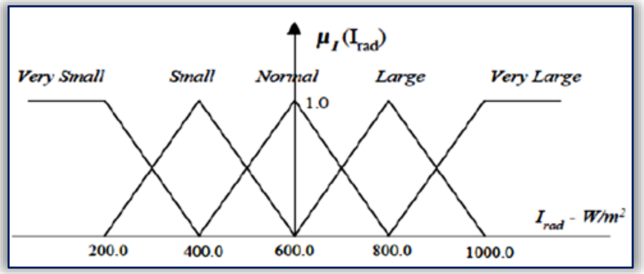

Figure 4. Solar radiation membership function

Table 1. Switch fuzzy rules

T_{in} \ I_{rad}		200 (VS)	400 (SM)	600 (NO)	800 (LA)	1000 (VL)
VS	100	C1	C2	C3	C4	C5
SM	125	C6	C7	C8	C9	C10
NO	150	C11	C12	C13	C14	C15
LA	175	C16	C17	C18	C19	C20
VL	200	C21	C22	C23	C24	C25

Looking at the system's responses to different workstations, we can see that some of them are very close. Due to this issue, the number of models considered can be reduced by classifying the models. Table 2 shows the result of this, which includes the new rules.

The fuzzy system is defined as follows according to the Takagi-Sugno rule:

Rule i: *if* $(I_{rad}$ *is* $SI^{(i)})$ *and* $(T_{in}$ *is* $ST^{(i)})$ *then,*

$$\alpha_i = \mu_I^{(i)}(I_{rad}) * \mu_T^{(i)}(T_{in})$$

In the expression $SI^{(i)}, i = 1,\ldots,7$ and $SI^{(i)}$ is the linguistic values expressed for the T_{in} and I_{rad} variables for rule i^{th}

— **Modeling the field of the parabolic solar collectors**

Due to the fact that the response of system to the step input is s-shape, a three-parts model in form of $G_{3\alpha}(s) = \frac{ke^{-sl}}{Ts+1}$ is used to approximate it [21]. To do this, the line tangent to the response curve with the highest slope is calculated and intersect with the line that determines the value of the final state to obtain the parameters of the three-parts $(G_{3\alpha}(s))$ model [22]. The models of P_i which $i = 1,\ldots,7$ should be obtained based upon system's perturbations.

Table 2. Simplified rule table for fuzzy switch

T_{in} \ I_{rad}	200	400	600	800	1000
100	C5	C5	C2	C6	C6
125	C5	C1	C5	C2	C2
150	C7	C5	C1	C4	C2
175	C7	C2	C4	C3	C4
200	C6	C7	C1	C4	C3

2. DESIGN OF PID IN PARALLEL WITH FEEDFORWARD CONTROLLER

According to what has been said, it is essential to prevent saturation of the control signal. However, the presence of an integrator in the PID controller can be a factor in saturating the control signal because it integrates the error signal, and as a result, its output value increases over time until of saturation. The saturation of integrator leads to the saturation of control signal and operator. Normally, to eliminate the saturation state, we must wait for the possible negative error to decrease the input value of the integrator. However, it could take a long time which would have adverse effects on the system. Anti-Windup circuit is one of the methods to prevent saturation and its adverse effects. The figure 5 shows the block diagram of a PID controller based on Anti-windup circuit.

In addition to prevention of the saturation of the integrator, PID with Anti-windup circuit can help to track the input signal and perturbations.

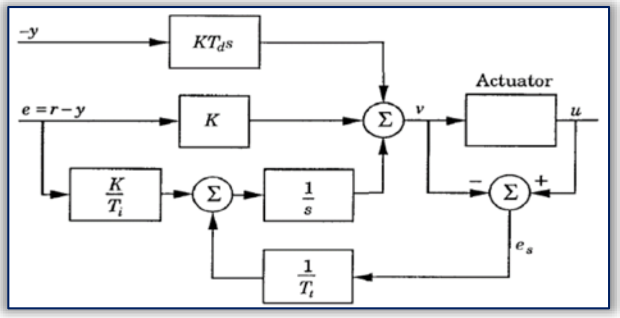

Figure 5. PID controller with Anti-Windup circuit

The design is based upon Ziegler-Nichhols [23]. To design the feedforward controller, it is necessary to obtain the mathematical model which be able to describe the input perturbations. The parallel and series feedforward comparators have many applications in industry. To obtain the equation, the energy balance equation for solar collectors according to concentration parameter has been derived (see the equation 4). By substituding 4 in the equation 5 and ordering the parameters, the equation 6 has been obtained which is used to design the feedforward controller.

$$c\frac{dT}{dt} = \eta_0 SI - \dot{q}\, p_{cp}(T - T_{in}) - H_l(T_m - T_a)(T - T_{in}) \tag{4}$$

$$u = \frac{1}{p_{cp}}(\eta_0 SI - H_l(T_m - T_a)) \tag{5}$$

$$u_{ff} = (\eta_0 SI - H_l(T_m - T_a)) / (p_{cp}(T - T_{in})) \tag{6}$$

After replacing the parameters, the main equation to design feedforward controller for the field of distributed parabolic solar collector will be as follow (the equation 7).

$$u_{ff} = (0.7869I - 0.485(T_{ref} - 151.5) - 80.7) / (T_{ref} - T_{in}) \tag{7}$$

The basic structure of feedforward controller is shown in figure 6, which according to this relation the variable of the system were defined. The variable u_{ff} is calculated flux to maintain the desired output temperature (T_{ref}) for dominant I, T_{in} and $q(t) = u(t) + u_{ff}(t)$. Indeed, required flux for the pump is equal to the sum of correlation in feedback and feedforward. The signal of u_{ff} varies to achieve the desired value in a stable condition when there is a perturbation in variables I and T_{in}.

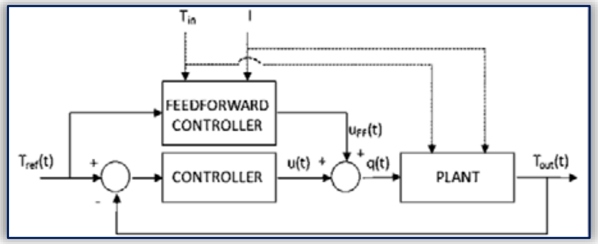

Figure 6. The block diagram of PID with parallel feedforward controller

3. RESULTS AND DISCUSSION

The presence of feedforward controller, which is parallel to PID, could have a suitable performance against system's perturbations. The figure 7 depicts a comparison between the responses of PID without feedforward controller and PID with a parallel feedforward controller in the structure of a fuzzy supervisor for a specific operating condition without perturbations.

The use of scheduled fuzzy controller is a good solution to eliminate the effects of perturbations in the field of solar collectors.

The figure 8 shows the response of system to the perturbations. T_{out1} is the response of the system by using PID with parallel feedforward controller and constant parameters and T_{out2} is the response of system by using fuzzy supervisor over PID with parallel feedforward controller in the precense of perturbations. A comparison between control signal of controller with and without scheduled fuzzy supervisor Q_{in1} and Q_{in2}, respectively, is demonstrated in figure 9.

The performance of fuzzy supervisor against perturbations is shown in figure 10. The stability against input perturbations and using multiple controllers simultaneously are advantages of scheduled fuzzy controllers. This structure makes it possible to utilize a fuzzy PID in one operating area and another PID with parallel feedforward controller in another area.

The figure 11 shows a comparison between the responses of the PID system with and without feedforward controller at $T_{in} = 170°c$ and $I_{rad} = 800\ \frac{W}{m^2}$. On the other hand, the figure 10 demonstrates the performance of controllers in only one operating condition, without perturbations and based on reference temperature represents one operating condition.

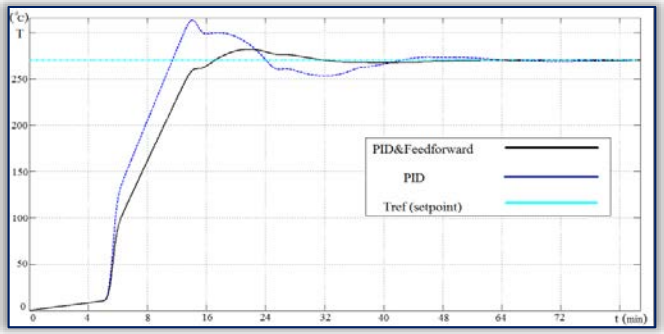

Figure 7. Comparision between controlling system with and without feedforward controller in one operating condition

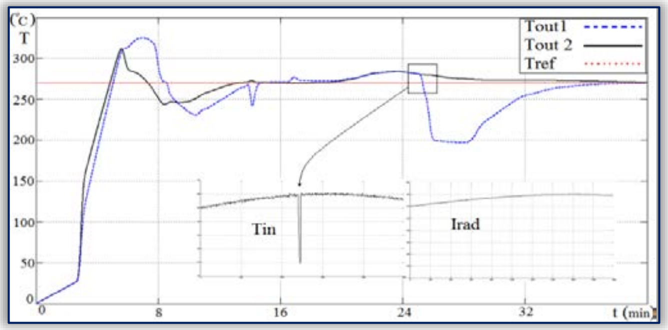

Figure 8. The performance of scheduled fuzzy supervisor against perurbations

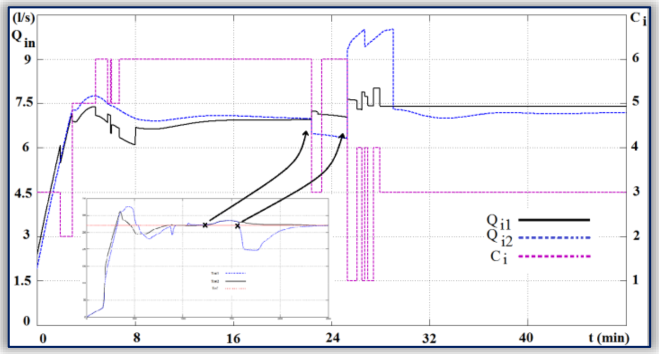

Figure 9. Comparisions between different control signals (Q_{in}) with switching

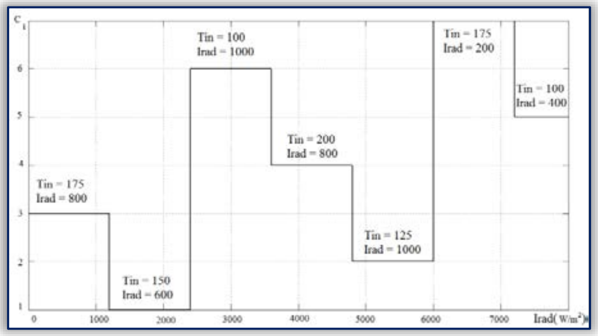

Figure 10. The performance of sqwitch in fuzzy controller

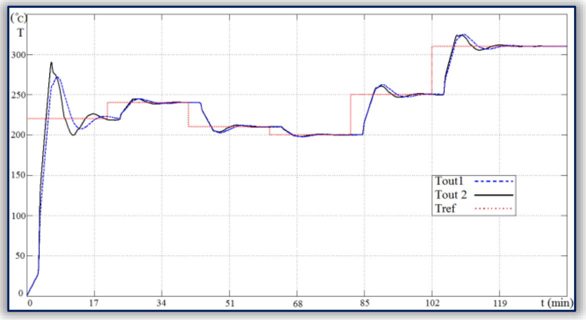

Figure 11. The performance of PID with and without feedforward controller in different operating conditions

This figure can compare controllers in one equal operating condition. As it can be seen, the precesnse of fuzzy supervisor in parallel with PID improves the response of the system matter of exaltation and stabilization. However, it should be noted that the importance of PID with parallel feedforward controller is more apparent in the presence of the perturbations.

4. CONCLUSION

Using the scheduled fuzzy controller in parabolic solar collectors enhances the performance of the system against perturbations caused by variation of environment condition. However, this is available only if a suitable controller is used based on different operating condition. Due to significant effect of perturbations on performance of the system, a feedforward controller was used in parallel to PID to increase robustness of the system against the relevant perturbation.

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