Computational Intelligence in Electrical Engineering
Vol. 12, No. 4, 2022
Research Paper

Adaptive Nonlinear Control of Outlet Oil Temperature of a Distributed Solar Collector Field in Presence of Environment Disturbances

Niloufar Maleki[1], Mahdi Khodabandeh[*2], Mohammad Soofi[3]

[1] Department of Electrical Engineering, Hamedan University of Technology, Hamedan, Iran
enj.maleki@gmail.com
[2] Department of Electrical Engineering, Hamedan University of Technology, Hamedan, Iran
khodabandeh@hut.ac.ir
[3] Department of Electrical Engineering, Hamedan University of Technology, Hamedan, Iran
msoofi68@gmail.com

Abstract :
In this paper, a high-performance controller is proposed for distributed solar collector field as the smooth signal control of this controller can achieve a fast response and low chattering. The purpose of this research is to adjust the outlet oil temperature of the collectors, despite the influence of uncertainties such as the impossibility to manipulate the primary energy source (unlike fossil power plants), variable oil temperature along the tube line, and the dirty surface of the mirrors as well as variable atmospheric conditions such as cloudy weather, air pollution, air humidity, and variations in sunlight. The main part of this paper is the presentation of a nonlinear controller for tracking the reference temperature value and adjusting the outlet oil temperature. For resolving distortion and chattering in the control signal, an adaptive controller is used to adjust the control parameters. The very smooth and well-adjusted control signal is the strength of this controller that can be practically applied to a linear parabolic solar power plant. Finally, while changes in solar radiation are considered a disturbance, the designed controller performance is studied in reference trajectory tracking and the results are presented in comparison to the non-adaptive nonlinear control.

Keywords: Adaptive Control, Linear Parabolic Distributed Solar Collector Field, Nonlinear Control, Solar Energy.

1. Introduction

Nowadays, solar energy is exploited for various purposes such as refrigeration, detoxification, water sweetening, etc. Solar energy is the most plentiful sustainable source of energy that sends more than 150,000 T.W of energy to the earth. The atmosphere reflected half of this energy, and the earth’s surface absorbs the other half. Only a little fraction of solar energy will be enough to meet the world's energy demand [1].

There are several ways, directly such as photovoltaic systems or indirectly, to convert solar energy into electrical energy. Indirect use of

---

[1] Submission date:15, 01, 2022
Acceptance date: 25 , 04, 2022
Corresponding author: Mahdi Khodabandeh, Department of Electrical Engineering, Hamedan University of Technology

10.22108/ISEE.2022.132335.1538

solar thermal energy is more for homemade, industrial, and power plant uses. Electric power generators are used in all power plants, such as hydropower plants, steam power plants, and gas power plants. A generator is a device that converts mechanical energy into electrical power. In solar power plants, the main task of the solar system (that's called collector) is to produce the steam needed to rotate the turbines. The collector is a structure on which the mirrors are placed and focuses the sun's radiation on the center of the fluid carrier tube. The power generation cycle of a solar collector plant is illustrated in Fig. 1.

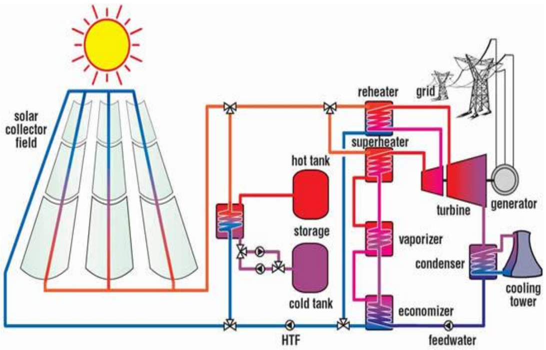


Fig. 1. Electricity generation cycle in solar collector power plant

The solar collector field has a tracking system that follows the sun from the east to the west [2]. Fluids used in solar collectors may be air, water, oil, or other organic solvents. Solar collectors have different types such as Fresnel lens concentrating collectors, compound parabolic collectors, flat-plate collectors with reflectors, and parabolic trough collectors (PTC)[1]. The purpose of the control in this system is to hold the output oil temperature at a favorable level notwithstanding disturbances such as changes in radiation, changes in the reflection of mirrors due to the presence of dirt, ambient temperature changes, and Inlet oil temperature, etc. Of course, the most important factor influencing these systems is solar radiation, and, directly or indirectly, other factors can be dependent on this factor. The temperature of the outlet oil for use in steam turbines should usually be above 285 °C; also to prevent the absorption of the tube material, the discord between the inlet and outlet temperatures of the oil should not exceed 80 ° C. If the temperature difference is more significant than this, the oil may leak because the oil pressure is high [2].

Table (1): Symbols

Description (Units)	Symbol
Tube related	$*_m$
Oil related	$*_f$
Density $\frac{kg}{m^3}$	ρ
Special heat capacity $\frac{J}{kg^oC}$	C
Area m^2	A
Diameter of mirror opening m	G
Inner diameter of transmission m	D
Differential tube length cm	Δl
Diameter of collector opening m	D_C
Flow of oil $\frac{kg}{S}$	q
Effective level of collectors	S
Temperature ^oC	T
Environment temperature ^oC	T_a
Time (second)	t
Set point temperature ^oC	T_{des}
Solar Irradiation $\frac{w}{m^2}$	$I(t)$
Space m	x
Mirror optical efficiency	η_o
Global coefficient of thermal losses $\frac{w}{m^{2o}C}$	H_l
Heat transfer coefficient between oil & tube $\frac{w}{m^{3o}C}$	H_t

Two categories of control methods, basic and advanced control, are used for distributed solar collector fields. PID control, feed forward control, and cascade control are among the basic controllers used in these power plants. Proposed methods for controlling distributed solar collector fields by the year 2007 have been studied in [3]. PID control is recognized as one of the most used controllers in the industry. The use of PID control with fixed parameters was investigated in 1987 by Camacho et al [4], but they were not able to reach a good performance of the system without the additional compensator in the control loop [5]. Actually, in all experiments, a PID control combined with a feed forward controller which is used to compensate for the effect of measurable disturbances has been applied [6]. In [7, 8], both dynamic and static feed forward terms have been developed. The combination of the PID and feed forward controller is the basis of a new generation of direct steam-generating solar power plants [9, 10]. The PI controller provided in [11] presents robust behavior. In addition, this controller can be an easy-to-use controller.

By splitting the control problem into two control loops, an inner control loop (slave) to compensate for disturbances and the outer control loop (master) to control the process output, cascade control can be developed to cancel the effects of the disturbances[3].

Because of the nonlinear nature of the system and the variety of disturbances, the use of base controllers would not be appropriate for model-based approaches. Therefore most researchers have sought to control this system using more advanced controllers. Several advanced control methods, such as robust control or adaptive control, have been developed around linear control systems. Some of the other control methods such as neural network control and fuzzy control developed around artificial intelligence control. In [12] the same feed forward controller and identification mechanism were presented in a comparative predictive control. Based on a simplified transfer function of the model, an adaptive robust predictive controller is developed in [13]. In [14] by using a simplified transfer function model that part of it includes resonance features, the alternative control plan was designed. This controller has been developed in [15]. An optimal control formulation is suggested in [14, 16] for achieving maximum efficiency of electricity production in the framework of controlling distributed collector systems. In 1985-1986 an alternative method by using a second-order Lyapunov function and adapting the law of control was proposed by Camacho et al [17, 18]. In [3, 19], the response of the system is divided into the forced and free terms and a model predictive control (MPC) is presented. Therefore, the effect of disturbances is taken into account using a nonlinear model of the free response, and the optimal sequence of control actions is obtained without a need for numerical methods. Also, by using a simplified mathematical model of the plant a nonlinear model-based predictive controller (NMPC) was designed [20]. This paper estimated the parameters of the nonlinear model. In [21] an adaptive feedback linearization scheme is proposed by benefiting from Lyapunov's rule. Some of the techniques for designing feedback systems with a high degree of robustness have been proposed by Camacho et al. [20]. In [22] by the reference temperature as the only system input, a nonlinear system subjected to disturbances, is controlled as an uncertain linear system. Then a feed forward controller is used as a robust controller [3]. In [23] the PDE field description is approximated by a compact parameter model. In [24] by using a simple feed forward method an automatic control approach was developed. In [19] various methods of advanced control including adaptive control, predictive controller, nonlinear internal controller, fuzzy control and optimal control have been investigated. In the context of these types of systems, the fuzzy control for controlling distributed solar collector field is considered from the outset. In [25], the use of supervisory fuzzy predictive control has been performed. Also a smart predictive controller besides the same mentioned idea has been used in [26, 27]. In [28] a fuzzy prediction control scheme is developed and in [29], a recursive neural network is used to obtain an overnight inverse of the system by applying fuzzy logic controller techniques.

Of course, in the most recent research, we can mention the Takagi Sugeno fuzzy model in which the nonlinear behavior of the system is identified and predicted [30]. Ref. [31] for solar trough systems proposed an observer-based model predictive control strategy, and the performance of the proposed control strategy is compared to a PID controller and a gain scheduling generalized predictive controller. A nonlinear predictive controller is also used in [32] and in [33] a solar power plant is described by partial differential equations and sliding mode control is applied to it. In [34], For solar thermal power generation system with fast time-varying, strong interference, and uncertainty characteristics, combined with compensatory the feed forward compensation to measurable disturbance, strong robustness of sliding mode control, and the advantages of predictive control to handle obvious constraints effectively, a method of feed forward sliding mode predictive controller is put forward to apply in solar thermal power generation heat collecting system. In the latest research, it is possible to provide optimal control in [35]. Increasing the electricity generated is the main objective of the above control strategies. Also, in [36] using PI control with feed forward control and using optimal control strategy, it has been tried to keep the production of electric power at desired set point during the day with partial radiation. In [37], the output oil temperature control is presented using the filter dynamic matrix control (FDMC). In [38], a novel strategy in oil temperature control is presented using the combination of parametric uncertainty robust control and the Takagi-Sugeno fuzzy model. In [39], a multi-model active fault-tolerant controller is established through the recursive least square method. A nonlinear controller has been designed in [40] to track reference temperature and its stability has been proven by Lyapunov's case. Of course, the existence of chattering in the control signal for this system is very clear. In the latest investigates, parabolic trough collector (PTC) and linear Fresnel reflector (LFR) are comprehensively and comparatively reviewed in terms of historical background, technological features, recent advancement, economic analysis, and application areas [41] and a detailed review of the experimental and numerical works carried out on heat transfer enhancement techniques which focus on minimization of heat loss, is presented in [42]. All the disturbances, including external disturbances and internal disturbances, were lumped into one disturbance and this disturbance is estimated and rejected by an active disturbance rejection control (ADRC) [43]. In [44], a feed forward-based strategy is proposed to control the outlet temperature of the collectors of a solar plant using the defocus angle as the manipulated variable. Predicting transformer oil temperature, in [45] had been investigated to accurately get the running state of transformer.

Inspired by the aforementioned research, the adaptive nonlinear control is investigated to adjust the outlet oil temperature of the collectors in this paper. In the control design, a high-performance controller is proposed for distributed solar collector field as the smooth signal control of this controller can achieve a fast response and low chattering. Compared with the existing studies, this work has two distinct characteristics:

Contrary to the works in [5, 7-10], a strong control is presented against uncertainty and disturbance in distributed collector system utilizing by robust nonlinear control method and Lyapunov approach.

In addition to guaranteeing the robustness of the designed controller, the proposed controller has a smooth signal control that can achieve a fast response and low chattering.

In the next section, system modeling and various numerical models presented for linear parabolic solar power plants are discussed and two models are used: a) distributed parameter model, and b) concentrated parameter model. In Section 3, first, a nonlinear controller is designed and next, an adaptive nonlinear controller is designed to control the output oil temperature of this plan and its stability has also been proven. Finally, Section 4 presents the simulation results of the control method based on the parameters of the Shiraz solar power plant which shows the proper performance controller. Concluding remarks are provided in section 5.

2. Mathematical Modeling and System Description

Several methods for numerical modeling of distributed solar collector power plants are found in the literature which was accepted [46]. Most of these models are obtained by experiments and the behavior of the ACUREX solar collector field. The main task of modeling the ACUREX was done by Carmona [47] and introduced in 1997 by Camacho. It should be noted in the modeling of a solar collector that a part of the concentrated radiation is absorbed by the oil and the other part is lost through metal tubes and glass. Given the thermal conductivity above the metal tube, we assume that the surface temperature inside and outside them is equal. Generally, the models presented for the solar collector field can be divided into two categories: "Fundamental models" and "Data-driven models". In the fundamental model, the dynamic field equation is achieved by the dynamic equations for each path, which are as follows:

$$\begin{aligned}&\rho_m C_m A_m \frac{\partial T_m}{\partial t}(t,x)=\\&\eta_0 GI(t)-p_{rc}-D\pi H_t\left(T_m(t,x)-T_f(t,x)\right)\end{aligned} \tag{1}$$

Where

$$p_{rc}=D_C\pi H_l\left(T_m-T_a\right) \tag{2}$$

Eq. (1) describes the energy absorbed by the oil tube, the energy lost to the environment, and finally the energy transferred to the oil. The amount of energy absorbed by the oil follows another dynamic equation:

$$\begin{aligned}&\rho_f C_f A_f \frac{\partial T_f}{\partial t}(t,x)+\rho_f C_f q(t)\frac{\partial T_f}{\partial x}(t,x)=\\&D\pi H_t\left(T_m(t,x)-T_f(t,x)\right)\end{aligned} \tag{3}$$

Some papers have proposed an energy equilibrium model that does not consider heat loss and has been used by some researchers. This equation is described as follows [48].

$$A\frac{\partial T}{\partial t}(t,x)+q(t)\frac{\partial T}{\partial x}(t,x)=\frac{\eta_0 G}{\rho C}I(t) \tag{4}$$

Depending on how the equations are solved, different equations can be presented based on the obtained data. In this paper, the "centralized parameter model" is used to design the controller, and the "distributed parameter model" is used to perform the simulation study.

2.1. Centralized Parameter Model

The Centralized parameter model is used to represent the total energy changes of the field using a compact equation. The values of the parameters used in this equation are calculated by the least-squares identification method in [49] and the centralized parameter model is presented as follows:

$$C_f\frac{dT}{dt}=\eta_0 SI(t)-q\rho_{cp}\left(T-T_{fin}\right)-H_l\left(T_{av}-T_a\right) \tag{5}$$

In this equation, T is output oil temperature, T_{fin} is inlet oil temperature, T_{av} is average inlet and outlet oil temperature, ρ_{cp} is the function of temperature, and the other parameters are described in Table 1. Due to the simplicity and absence of complex parameters in this equation as well as a relatively accurate representation of the amount of system energy, this equation is more commonly used for control purposes and is less used to express the complete and accurate behavior of the system.

2.2. Distributed Parameters Model

The dynamics of the distributed solar collector field is the description of the energy equilibrium by partial differential equations. Dynamic field equations are obtained by writing the dynamic equations of each path. These equations are given in equations (1) & (3). Several methods have been proposed to solve them such as the method of line, finite difference method, partial iteration process, and so on. The general idea of most partial differential equation solving methods is that the continuous domain of the problem is discretized at first. Then the unknown function or its derivatives are approximated by a numerical technique (in fact, the difference between the different methods is due to the difference in the type of approximation used). Combining the discrete and the approximate equations converts the differential equation to a matrix equation that by solving it, the solution of differential equations is obtained.

$$\begin{aligned}&\rho_m C_m A_m\frac{\partial T_{mi}}{\partial t}(t,x)=\\&\eta_0 GI(t)-p_{rc}-D\pi H_t\left(T_{mi}(t,x)-T_{fi}(t,x)\right)\end{aligned} \tag{6}$$

$$\begin{aligned}&\rho_f C_f A_f\frac{\partial T_{fi}}{\partial t}(t,x)+\rho_f C_f q(t)\frac{T_{fi}(t,x)-T_{f(i-1)}(t,x)}{\Delta l}=\\&D\pi H_t\left(T_{mi}(t,x)-T_{fi}(t,x)\right)\end{aligned} \tag{7}$$

In these equations, i represents the collector number used in the Distributed Solar Collector Field. It should be noted that the equations apply only to the active regions. In this equation, in addition to total system efficiency, optical efficiency is also considered. η0 as optical efficiency is one of the important parameters in this system which is a function of optical properties (mirror reflection coefficient, glass tube crossing coefficient, and receiver tube absorption coefficient) and angle of impact (the angle created between sunlight and the line perpendicular to the collector surface) [50]. The optical efficiency of the parabolic trough collector (PTC) is calculated by the following equation [51]:

$$\eta_0=\rho(\tau\alpha)_n\gamma K(\theta) \tag{8}$$

The parameter ρ represents the reflectivity of the mirror, (τα) is the natural absorption and transfer factor, γ is the coefficient of determination, and K(θ) is the angle-modifier coefficient of radiation, which is a function of hours and days of the year. To calculate this parameter, the collector efficiency at each angle is calculated first [51, 52]:

$$\cos(\theta)=\sqrt{\cos^2(\theta_z)+\sin^2(\omega)\cos^2(\delta)} \tag{9}$$

$$\omega=15(t-12) \tag{10}$$

$$\delta=23.45\sin\left(360\frac{(284+N)}{365}\right) \tag{11}$$

$$\cos(\theta_z)=\sin(\delta)\sin(\varphi)+\cos(\delta)\cos(\varphi)\cos(\omega) \tag{12}$$

N represents the number of days, φ is the geographical width of the solar collector field, θ_Z is the angle of the sun's peak, δ is the angle of deviation, θ is the collision angle and *t* is time in hours. Using the values obtained by the above equations, K(θ) is calculated by the following equation [53, 54]:

$$K(\theta)=cos(\theta)-0.0006586290\theta-0.0007581240\theta^2 \tag{13}$$

Also the coefficient of heat transfer is calculated by the following equation:

$$H_t=0.1882-8.304\times10^{-5}(T+273.15) \tag{14}$$

3. Control Design

Since oil temperature and pressure are the main factors in generating electricity for these types of solar power plants, an appropriate controller should be designed and used to adjust the temperature and optimize the operation of the power plant. Excessive oil temperatures can cause damage to existing equipment and hardware. On the other hand, lowering the oil temperature has a direct effect on reducing energy generation efficiency. The purpose of control in this paper is to regulate the temperature of the oil output from the solar collector despite the disturbances. For this purpose, a sliding mode controller was first designed to track the reference temperature, and then an adaptive term is added to the controller to have a robust and applicable controller in real-time conditions.

3.1. Nonlinear Controllers

The purpose of the controller design in this section is to track the desired temperature. A reference temperature is considered to control the temperature of the oil under various conditions depending on factors such as the amount of sunlight, the dynamical conditions of the system, the amount of oil temperature required to generate electrical energy, and many other factors and also it is tried to keep the oil temperature within the desired range. In most of these power plants, the reference temperature is set by human operators, but in some papers, intelligent controllers such as the fuzzy controller or neural network controller have been used to calculate the reference temperature.

To design the nonlinear controller, the tracking error is first defined and the control problem is changed to a tracking problem, and by using Lyapunov's theory, control conditions and rules are calculated so that the tracking error converges to zero or at least stays in a confined area.

$$e(t)=T_{des}-T \tag{15}$$

T_{des} is the reference temperature, which according to the system conditions must be achievable and T is the temperature of the output oil of the system. By differentiating (15) and replacing (5) the following equation is obtained:

$$\dot{e}(t)=\dot{T}_{des}-\dot{T}=$$

$$\dot{T}_{des}-\frac{\eta_0 SI-q\rho_{cp}\left(T-T_{f_{in}}\right)-H_l\left(T_m-T_a\right)}{C} \tag{16}$$

It can be further shown that by applying (17) as an input of the system (flow rate of the oil), the error is converges to zero, where k(t) is a time-varying control gain which satisfies the robustness condition which is presented in continue.

$$q=-k(t)e(t)\left[sgn\left(T-T_{f_{in}}\right)\right] \tag{17}$$

Proof: Lyapunov's theory is used to prove the stability of the designed controller. Therefore, a positive Lyapunov function is defined as follows.

$$V_1(t)=\frac{1}{2}e^2(t) \tag{18}$$

Using equation (16) the following result is obtained:

$$\dot{V}_1(t)=e(t)\dot{e}(t)=$$

$$e(t)\left[\dot{T}_{des}-\frac{\eta_0 SI-q\rho_{cp}\left(T-T_{f_{in}}\right)-H_l\left(T_m-T_a\right)}{C}\right] \tag{19}$$

And then by substituting the control signal presented in equation (17), equation (19) is reached as:

$$\dot{V}_1(t)=e(t)\left[\dot{T}_{des}-F\right]-\left[k(t)Ge^2(t)\right] \tag{20}$$

Where the functions F and G are defined as follows:

$$F=\left[\frac{\eta_0 SI-H_l\left(T_m-T_a\right)}{C}\right] \tag{21}$$

$$G=\left[\frac{\rho_{cp}}{C}\left|T-T_{f_{in}}\right|\right]\geq 0 \tag{22}$$

If the control gain, k(t), is given by equation (23), the robustness condition will be met.

$$k(t) > \left|\frac{\dot{T}_{des} - F}{G}\right| . \left\{\frac{sgn(e(t))}{e(t)}\right\} \quad , \quad e(t) \neq 0 \tag{23}$$

Then:

$$\begin{aligned} & k(t)Ge^2(t) > \\ & \left|\dot{T}_{des} - F\right| . \left\{e(t)sgn(e(t))\right\} = \\ & \left|\dot{T}_{des} - F\right| \left|e(t)\right| \geq \left\{\dot{T}_{des} - F\right\} e(t) \end{aligned} \tag{24}$$

Hence, the control objective has been achieved that is:

$$\dot{V}_1(t) < 0 \qquad for \quad e(t) \neq 0 \tag{24}$$

Due to the negative derivative of the Lyapunov's function, thus the output tracking error e(t) converges to zero.

Remark 1: It should be noted that the disturbances in this system are considered by solar radiation or are related to some of the parameters, for example (η_0) in (equation (8)) [33, 35, 38]. Therefore, if inequality (23) is satisfied for any F and G, the controller is robust against disturbances, and the convergence of tracking error is guaranteed with Lyapunov’s theorem.

Remark 2: It should be noted that equation (23) guarantees the robustness condition for the developed sliding mode controller and in practice, choosing K is difficult at all times. However, one can choose K arbitrarily large to satisfy equation (23) at all times but this can cause chattering in the input signal. This problem is discussed in the next remark. Since the objective of the designed controller is reference temperature tracking and to achieve the minimum error possible, at e(t)=0, K(t) can have its minimum value.

3.2. Adaptive Nonlinear Controller

As it is explained in the previous section, calculating the control gain at all times increases the computational time and leads to further complexity of the controller. For this reason, the control gain is usually considered a constant and sufficiently large amount. However, it should also be kept in mind that by changing environmental conditions, disturbances, and even minor changes to the system such as increasing or decreasing the number of collectors, partial failure of the system and, so on, the control gain should also be changed to maintain system stability on the one hand and to prevent chattering on the other hand. The magnitude of the created chattering depends on the control gain value. To resolve this issue, various methods are used, including continuous approximation and high-order nonlinearity, which is a method for improving nonlinear accuracy, and chattering and combinatorial methods [1]. One of the combined methods is the use of adaptive control to regulate the controller gain. Adding the adaptive part to nonlinear control in addition to helping optimum chattering, can improve the robustness against uncertainty and disturbances and also has a higher convergence rate in comparison to the conventional methods. In this paper, nonlinear control and adaptive control are combined to design a controller that performs better. In fact, the adaptive controller is used to adjust the control gain in the designed controller. Therefore, with changes to the control signal equation (17), the new control law is calculated as:

$$\begin{aligned} & q = -\hat{k}(t)e(t)\left[sgn\left(T - T_{f_{in}}\right)\right] \\ & -\beta e(t) sgn\left(T - T_{f_{in}}\right) \end{aligned} \tag{26}$$

Where $\beta \succ 0$ and $\hat{k}(t)$ is the adaptive rate. The adaptive law is chosen as follows to simplify and avoid complex calculations:

$$\dot{\hat{k}} = \frac{1}{\gamma}\frac{\rho_{cp}}{C} e^2(t)\left|T - T_{fin}\right| \tag{27}$$

It is obvious that the control signal has two general changes compared to the previous controller. First, instead of control gain, $k(t)$ the adaptive rate, $\hat{k}(t)$ is used which is easier to calculate. Second, a term has been added to the control law to ensure the system`s stability.

Proof: Same as in the previous section, a new Lyapunov function is defined:

$$V_2 = \frac{1}{2}e^2(t) + \frac{1}{2}\gamma\tilde{k}^2(t) \tag{28}$$

In this function, γ that is a positive constant is defined and $\tilde{k}$ is chosen as the adaptive error as follows:

$$\tilde{k}(t) = \hat{k}(t) - k \tag{29}$$

Here, k is assumed to be constant and arbitrarily large according to the conditions of the system. The time-derivative of the Lyapunov function can be obtained as:

$$\dot{V}_2 = e\dot{e} + \gamma\tilde{k}\dot{\tilde{k}} = e\dot{e} + \gamma\tilde{k}\dot{\hat{k}} \tag{30}$$

Then using equation (13):

$$\dot{V}_2 = e(t)\left[\dot{T}_{des} - \frac{\eta_0 SI - q\rho_{cp}\left(T - T_{fin}\right) - H_l\left(T_m - T_a\right)}{C}\right] + \gamma\tilde{k}\dot{\hat{k}} \tag{31}$$

By substituting equation (26) into equation (31):

$$\begin{aligned}\dot{V}_2 &= e(t)\left[\dot{T}_{des} - \frac{\eta_0 SI - H_l\left(T_m - T_a\right)}{C}\right] \\ &-\left(\beta + \hat{k}\right)\frac{\rho_{cp}}{C}e^2(t)\left|T - T_{fin}\right| + \gamma\tilde{k}\dot{\hat{k}}\end{aligned} \tag{32}$$

And by substituting $\tilde{k}$ and $\dot{\hat{k}}$ using equation (29) and equation (27), respectively:

$$\begin{aligned}\dot{V}_2 &= e(t)\left[\dot{T}_{des} - \frac{\eta_0 SI - H_l\left(T_m - T_a\right)}{C}\right] \\ &-\left(\beta + \hat{k}\right)\frac{\rho_{cp}}{C}e^2(t)\left|T - T_{fin}\right| \\ &+\hat{k}\left(\frac{\rho_{cp}}{C}e^2(t)\left|T - T_{fin}\right|\right) \\ &-k\left(\frac{\rho_{cp}}{C}e^2(t)\left|T - T_{fin}\right|\right)\end{aligned} \tag{33}$$

And by using equations (21)- (22):

$$\begin{aligned}\dot{V}_2 &= e(t)\left[\dot{T}_{des} - F\right] - \left(\beta + \hat{k}\right)e^2(t)G \\ &+\hat{k}e^2(t)G - ke^2(t)G\end{aligned} \tag{34}$$

$$\begin{aligned}\dot{V}_2 &= e(t)\left[\dot{T}_{des} - F\right] \\ &-\beta e^2(t)G - ke^2(t)G < 0\end{aligned} \tag{35}$$

Since in equation (24), $\left\{kGe^2(t) \succ (\dot{T}_{des} - F)e(t)\right\}$ and $\left\{\beta e^2(t)G\right\}$ is always positive, Therefore:

$$\dot{V}_1(t) < 0 \qquad for \quad e(t) \neq 0 \tag{36}$$

Therefore the output tracking error e(t) converges to zero.

In the next section, the proposed control strategies to track the reference temperature are studied for a distributed solar collector field using real data.

4. Simulation Results

Most of the distributed solar collector field power plants in the world have oil and steam cycles. The purpose of this paper is to control the temperature of the outlet oil in the collectors. In this section, the 250 KW power plant in Shiraz, which is a linear parabolic collector and the designed controllers have been implemented in MATLAB. The Shiraz power plant consists of 48 collectors that are in an area of 13500 m^2 and with 8 parallel directions and 6 collectors in each direction along the north-south U-path. The Behran heat transfer oil is used in the Shiraz solar power plant and the lowest and highest oil flow rates in the tubes are 2kg/s and 16kg/s, respectively. The oil is able to withstand heat up to 290^{o}C [54, 55]. The metal used for the construction of tubes is ordinary steel or carbon steel. Of course, the electrical-thermal efficiency of carbon steel is higher than that of ordinary steel [56]. In order to obtain more accurate results and evaluate the efficiency of the designed controller, the distributed parameters model which is mentioned in Section 2-2 is used. The numerical values of each of the parameters considered in the plant are given in Table 2.

Fig. 2 illustrates the effect of the control gain k in the designed controller in Section 3-1. Increased control gain makes tracking more accurate and better. In this controller, the gain control plays a decisive role in the steady state error of the system response and has almost no effect on the transient response of the system. Fig 3 shows a comparison between how the reference signal is tracked in the controller with constant k=1 (nonlinear controller (N.C.)) and the adaptive nonlinear controller (A.N.C.). As shown in the figure, both controllers track the reference temperature. Fig. 4 shows that the control signal in the controller has chattering, while the control signal in the adaptive controller is reasonably desirable. Also, the changing of adaptive gain K is shown in Fig. 5.

In real conditions, some natural factors cause the loss of solar energy and reduce the overall efficiency of the system. Some of these factors can include wreck to some mirrors and inadequate rotation to reflect sunlight, dirty mirror surfaces, dirty transmission tubes, etc. In some papers, a modification factor for the outlet oil temperature is chosen to match the simulated models to the real state. This modification factor which affects the sunlight differs depending on the environmental conditions of different days. To study the performance of the controllers, a real data simulation of the Shiraz solar power plant is compared with the results of the designed controllers. By trial and error it was founded that by choosing the modification factor of 0.35 for this day, the results of the modeling and the real state are similar.

Table (3 shows the condition of the power plant on this day.

Table (2): Parameters of the Shiraz solar collector field

Description	Value
Tube density	$7860\frac{kg}{m^2}$
Special heat capacity of tube	$450\frac{J}{kg^{\circ}C}$
Oil and tube area	$1.38544236\times10^{-3}m^2$
Diameter of mirror opening	$3.4m$
Inner diameter of transmission tube	$42m$
Heat transfer coefficient between oil and tube	$0.96\frac{w}{m^{3^{\circ}}C}$
Differential tube length	$25cm$
Diameter of collector opening	$5m$
Latitude of solar collectors field	$29^{\circ}C$
Oil density	$0.72-1071.76(T+273.15)\frac{kg}{m^2}$
Special heat capacity of oil	$3.706+813.2(T+273.15)\frac{J}{kg^{\circ}C}$

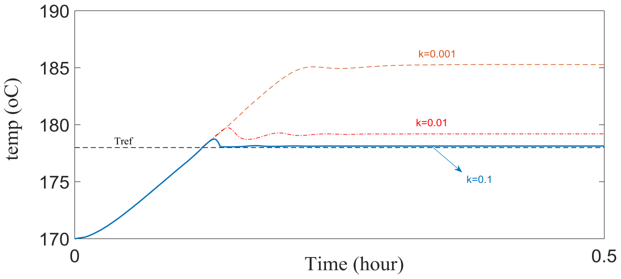


Fig. 2. Effect of the control gain k in the nonlinear controller

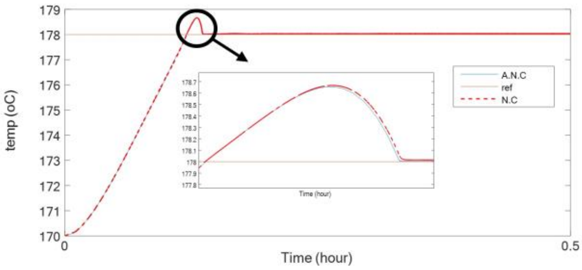


Fig.3. Temperature tracking by nonlinear controller (N.C.) and adaptive nonlinear controller (A.N.C,)

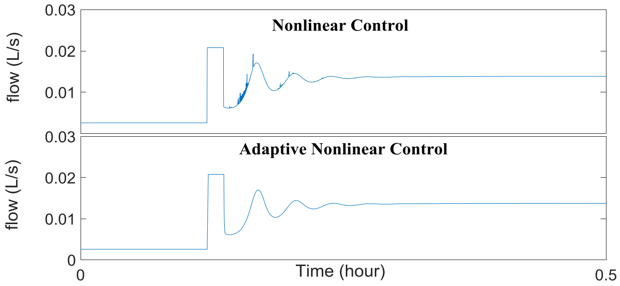


Fig. 4. Oil flow of Shiraz power plant

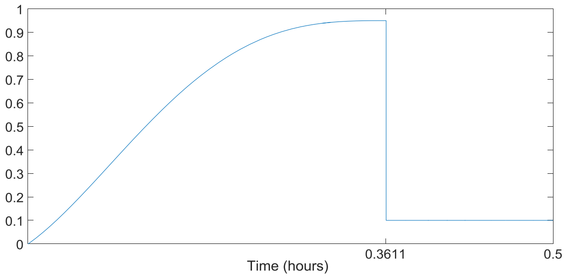


Fig. 5. Variations of the controller gain $|k|$ of the adaptive nonlinear controller

It should be noted that in the real state, the control system is regulated by an operator. Since the initial oil temperature is about 100°C in the early hours of the day and the optimum outlet oil temperature is 265°C, in the first time of tracking, the system is running at its minimum value. This is due to the difference between the input oil temperature and the reference temperature. An optimal curve control structure is used to solve this problem. In this way, the initial set point temperature of the system is selected 20 degrees higher than its input oil temperature, and when the temperature reaches the desired value, the desired value increases again to 20 degrees, and this process continues. Fig. 6 shows solar radiation in the city of Shiraz on November 14, 2010.

Fig 7 also shows a comparison between the controllers designed in this paper with the real state (operator-controlled). **Error! Reference source not found.** and Fig. 9 show the amount of oil flow in each control method and variation of control gain K in the adaptive nonlinear control scheme, respectively. As it is well known in the simulation results, the designed controllers have been able to achieve higher temperature at the output of the transmission tubes than the control mode by the operator.

In order to prove the claim that the designed controller is robust to disturbances entering the system, three different tests have been carried out. These tests depend on the intensity profile of the sunlight which is striking the solar collector. In this experiment, it was first assumed that solar radiation would be applied to the system in a normal state without any disturbance. The second test has been performed by using a varying profile with some rapid changes in the disturbances. The last test has been performed for the worst possible conditions, under unfavorable radiation. Test results are shown in Fig. 10.

As the test results show, the designed adaptive nonlinear controller is able to provide the desired response with a very smooth control signal and without chattering under different conditions.

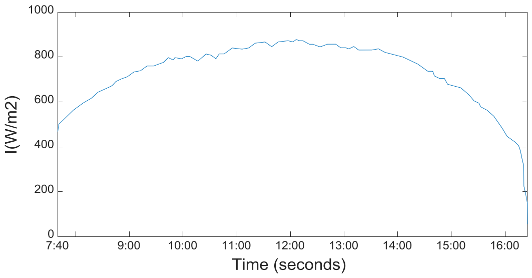


Fig. 6. Solar radiation in the city of Shiraz

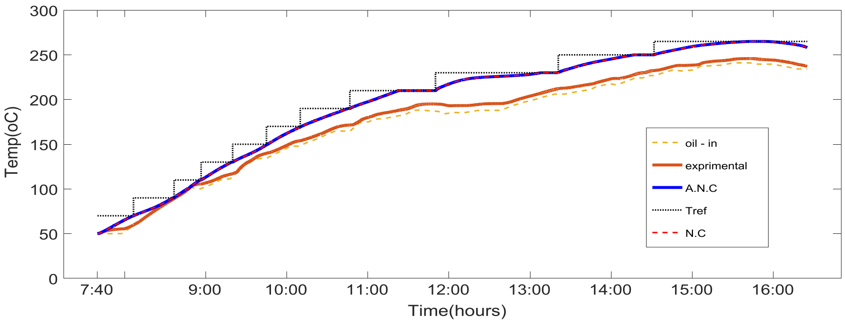
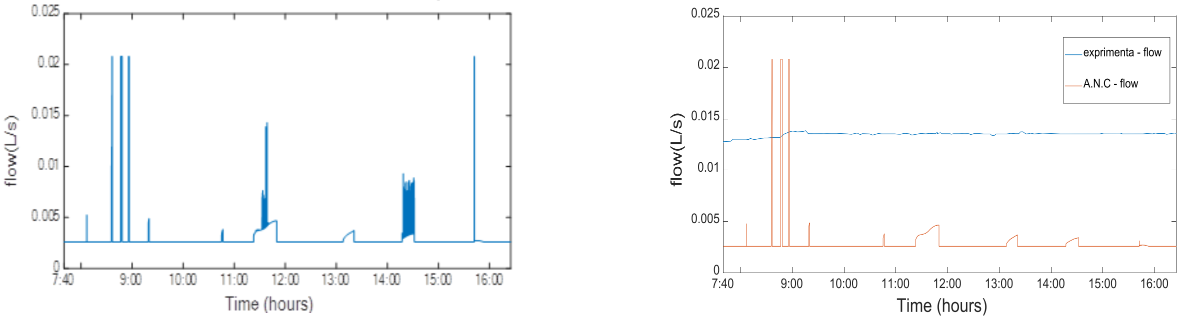


Fig. 7. Output oil temperature



(a) **(b)**

Fig. 8. Oil flow: (a) the control signal in real state and for designed adaptive nonlinear control, (b) the control signal for designed nonlinear control

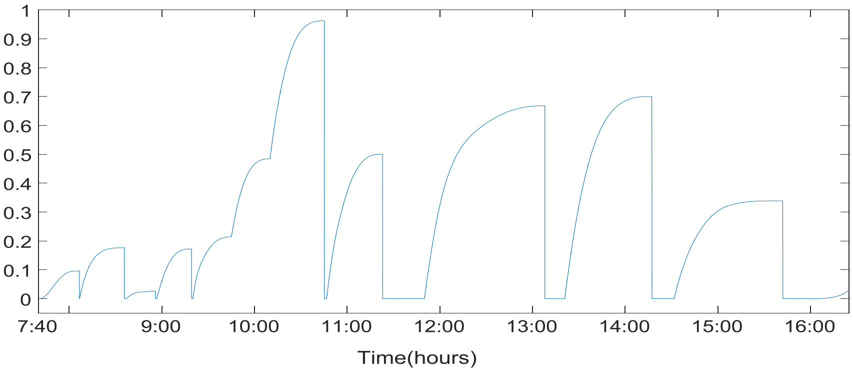
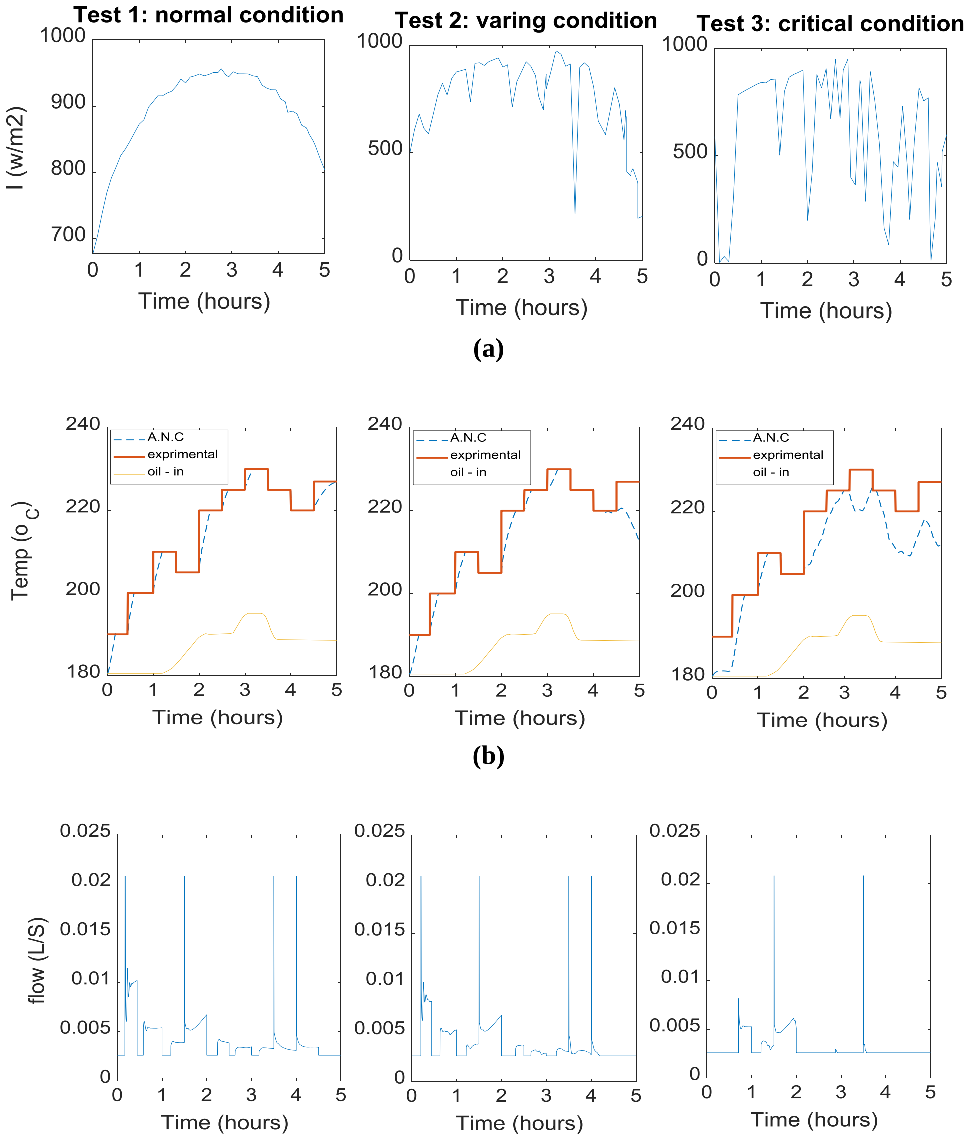


Fig. 9. Variations of the controller gain $|k|$ of the adaptive nonlinear controller



(a)

(b)

(c)

Fig. 10. Investigating the robustness of the controller under different working conditions. (a) Solar radiation, (b) Output oil temperature, (c) Oil flow

Table (3) Operational Conditions of the power plant

Start time tracking	8:00
End time tracking	16:45
Oil temperature at the start time	$52^{o}C$
Oil discharge at the start time	$12.12\frac{kg}{s}$
Number of circles traced	7 from 8 circles
Weather on the test day	Clear with a bit of cloud
Status of mirrors	dirty
Receiver tube status	Dirty
Correction factor in the simulation	0.35

5. Conclusions

In this research, it has been theoretically proved that a distributed solar collector field can be controlled by using a nonlinear controller with adaptive theory to increase the robustness and convergence speed and reduce the system chattering. First, a nonlinear controller is designed to track the set point temperature for the output oil. In this controller, there is a direct relationship between the control gain and temperature tracking performance, but an increase in control gain leads to chattering in the control signal. For this reason, an adaptive term has been added to the controller to address this problem. Finally, the simulation results using real day information at the 250 kW power plant in Shiraz showed better and more efficient performance of the proposed method.

References

[1] V. Jebasingh, G. J. Herbert, “A Review of Solar Parabolic Trough Collector”, Renewable and Sustainable Energy Reviews, Vol. 54, pp. 1085-1091, 2016.

[2] A. Gallego, E. F. Camacho, “Estimation of Effective Solar Irradiation Using an Unscented Kalman Filter in a Parabolic-Trough Field”, Solar Energy, Vol. 86, No. 12, pp. 3512-3518, 2012.

[3] E. F. Camacho, F. R. Rubio, M. Berenguel, L. Valenzuela, “A Survey on Control Schemes for Distributed Solar Collector Fields. Part I: Modeling and Basic Control Approaches”, Solar Energy, Vol. 81, No. 10, pp. 1240-1251, 2007.

[4] I. Farkas, I. Vajk, “Internal Model-based Controller for a Solar Plant”, IFAC Proceedings Volumes, Vol. 35, No. 1, pp. 49-54, 2002.

[5] M. Barao, J. Lemos, R. Silva, “Reduced Complexity Adaptive Nonlinear Control of a Distributed Collector Solar Field”, Journal of Process Control, Vol. 12, No. 1, pp. 131-141, 2002.

[6] L. Li, Y. Li, Y. L. He, “Flexible and Efficient Feedforward Control of Concentrating Solar Collectors”, Applied Thermal Engineering, Vol. 171, pp. 115053, 2020.

[7] M.D. España, L. Rodriguez, “Approximate Steady State Modeling of Solar Trough Collectors”, Solar Energy, Vol. 38, No. 6, pp. 447-454, 1987.

[8] E. F. Camacho, F. Rubio, F. Hughes, “Self-Tuning Control of a Solar Power Plant with a Distributed Collector Field”, IEEE Control Systems Magazine, Vol. 12, No. 2, pp. 72-78, 1992.

[9] L. Valenzuela, E. Zarza, M. Berenguel, E. F. Camacho, “Control Scheme for Direct Steam Generation in Parabolic Troughs under Recirculation Operation Mode”, Solar Energy, Vol. 80, No. 1, pp. 1-17, 2006.

[10] L. Valenzuela, E. Zarza, M. Berenguel, E. F. Camacho, “Control Concepts for Direct Steam Generation in Parabolic Troughs”, Solar Energy, Vol. 78, No. 2, pp. 301-311, 2005.

[11] J. E. Normey-Rico, C. Bordons, M. Berenguel, E. F. Camacho, “A Robust Adaptive Dead-Time Compensator with Application to a Solar Collector Field”, IFAC Proceedings Volumes, Vol. 31, No. 19, pp. 93-98, 1998.

[12] E. F. Camacho, M. Berenguel, C. Bordons, “Adaptive Generalized Predictive Control of a Distributed Collector Field”, IEEE Transactions on Control Systems Technology, Vol. 2, No. 4, pp. 462-467, 1994.

[13] E. F. Camacho, M. Berenguel, “Robust Adaptive Model Predictive Control of a Solar Plant with Bounded Uncertainties”, International Journal of Adaptive Control and Signal Processing, Vol. 11, No. 4, pp. 311-325, 1997.

[14] A. Orbach, C. Rorres, R. Fischl, “Optimal Control of a Solar Collector Loop Using a Distributed-Lumped Model”, Automatica, Vol. 17, No. 3, pp. 535-539, 1981.

[15] A. Meaburn, F. Hughes, “Resonance Characteristics of Distributed Solar Collector Fields”, Solar Energy, Vol. 51, No. 3, pp. 215-221, 1993.

[16] L. Valenzuela, P. Balsa, “Series and Parallel Feedforward Control Schemes to Regulate the Pperation of a Solar Collector Field”, Proceedings of the 2nd User Workshop Training and Mobility of Researchers Programme at Plataforma Solar de Almeria, 1998.

[17] L. Carotenuto, M. La Cava, G. Raiconi, “Regulator Design for the Bilinear Distributed-Parameter Model of a Solar-Power Plant”, International Journal of Systems Science, Vol. 16, No. 7, pp. 885-900, 1985.

[18] L. Carotenuto, M. La Cava, P. Muraca, G. Raiconi, S. Tzafestas., “Feedforward Control for the Distributed Parameter Model of a Solar Power Plant”, Large scale systems, Vol. 11, No. 3, pp. 233-241, 1986.

[19] E. F. Camacho, F. R. Rubio, M. Berenguel, L. Valenzuela, “A Survey on Control Schemes for Distributed Solar Collector Fields. Part II: Advanced Control Approaches”, Solar Energy, Vol. 81, No. 10, pp. 1252-1272, 2007.

[20] R. Pickhardt, “Nonlinear Modelling and Adaptive Predictive Control of a Solar Power Plant”, Control Engineering Practice, Vol. 8, No. 8, pp. 937-947, 2000.

[21] J. M. Igreja, J. M. Lemos, M., Barão, R. N. Silva, “Adaptive Nonlinear Control of a Distributed Collector Solar Field”, 2003 European Control Conference (ECC)”, 2003.

[22] C. Cirre, J. Moreno, M. Berenguel, “Robust QFT Control of a Solar Collectors Field”, IHP Programme, Research results at PSA within the year, pp. 27-33, 2002.

[23] J. M. Lemos, R. Neves-Silva, J. M. Igreja, “Adaptive Control of Solar Energy Collector Systems”, Vol. 253, Springer, 2014.

[24] C. M. Cirre, M. Berenguel, L. Valenzuela, E. F. Camacho, “Feedback Linearization Control for a Distributed Solar Collector Field”, Control Engineering Practice, Vol. 15, No. 12, pp. 1533-1544, 2007.

[25] R. Morales, F. Valencia, D. Sáez, M. Lacalle, “Supervisory Fuzzy Predictive Control for a Concentrated Solar Power Plant”, IFAC Proceedings Volumes, Vol. 47, No. 3, pp. 1459-1464, 2014.

[26] M. Jalili-Kharaajoo, F. Besharati, “Intelligent Predictive Control of a Solar Power Plant with Neuro-Fuzzy Identifier and Evolutionary Programming Optimizer”, 2003 IEEE Conference on Emerging Technologies and Factory Automation, EFTA 2003, Proceedings (Cat. No. 03TH8696), 2003.

[27] M. Jalili-Kharaajoo, “Predictive Control of a Solar Power Plant with Neuro-Fuzzy Identification and Evolutionary Programming Optimization”, Mexican International Conference on Artificial Intelligence, Springer, 2004.

[28] A. Flores, D. Sáez, D., J. Araya, M. Berenguel, A. Cipriano, “Fuzzy Predictive Control of a Solar Power Plant”, IEEE Transactions on Fuzzy systems, Vol. 13, No. 1, pp. 58-68, 2005.

[29] P. Gil, J. Henriques, A. Dourado, “Recurrent Neural Networks and Feedback Linearization for a Solar Power Plant Control”, EUNIT01, 2001.

[30] C. Ponce, D. Saez, A. Nunez, “Fuzzy Predictive Control Strategy for a Distributed Solar Collector Plant”, IEEE Latin America Transactions, Vol. 12, No. 4, pp. 626-633, 2014.

[31] A. J. Gallego, F. Fele, E. F. Camacho, L. Yebra, “Observer-based Model Predictive Control of a Parabolic-Trough Field”, Solar Energy, Vol. 97, pp. 426-435, 2013.

[32] G. A. Andrade, D. J. Pagano, J. D. Alvarez, M. Berenguel, “A Practical NMPC with Robustness of Stability Applied to Distributed Solar Power Plants”, Solar Energy, Vol. 92 pp. 106-122, 2013.

[33] G. A. Andrade, D. J. Pagano, J. D. Álvarez, “Sliding Mode Control of Distributed Parameter Processes: Application to a Solar Power Plant”, Journal of Control, Automation and Electrical Systems, Vol. 25, No. 3, pp. 291-302, 2014.

[34] X. J. Lu, H. Y. Dong, “Application Research of Sliding Mode Predictive Control based on Feedforward Compensation in Solar Thermal Power Generation Heat Collecting System”, International Journal of Hybrid Information Technology, Vol. 9, pp. 211-220, 2016.

[35] S. J., Navas, F. R., Rubio, P. Ollero, J. M. Lemos, “Optimal Control Applied to Distributed Solar Collector Fields with Partial Radiation”, Solar Energy, Vol. 159, pp. 811-819, 2018.

[36] S. J. Navas, F. R. Rubio, P. Ollero, “Optimum Control of Parabolic Trough Solar Fields with Partial Radiation”, IFAC PapersOnLine, Vol. 50, No. 1, pp. 109-114, 2017.

[37] D. M. Lima, J. E. Normey Rico, T. L. M. Santos, “Temperature Control in a Solar Collector Field Using Filtered Dynamic Matrix Control”, ISA Transactions, Vol. 62, pp. 39-49, 2016.

[38] A. Bayas, I. Škrjanc, and D. Sáez, “Design of Fuzzy Robust Control Strategies for a Distributed Solar Collector Field”, Applied Soft Computing, Vol. 71, pp. 1009-1019, 2018.

[39] X. Lu, H. Dong, “Application of Multi Model Active Fault Tolerant Sliding Mode Predictive Control in Solar Thermal Power Generation System”, Acta Automatica Sinica, 2017.

[40] S. Elmetennani,T.M. Laleg Kirati, “Bilinear Approximate Model-based Robust Lyapunov Control for Parabolic Distributed Collectors”, IEEE Transactions on Control Systems Technology, Vol. 25, No. 5, pp. 1848-1855, 2016.

[41] J. Sun, Z. Zhang, L. Wang, Z. Zhang, J. Wei, “Comprehensive Review of Line Focus Concentrating Solar Thermal Technologies: Parabolic Trough Collector (PTC) vs Linear

Fresnel Reflector (LFR)", Journal of Thermal Science, Vol. 29, No. 5, pp. 1097-1124. 2020.

[42] G Kumaresan, P Sudhakar, R Santosh., R. Velraj, "Experimental and Numerical Studies of Thermal Performance Enhancement in the Receiver Part of Solar Parabolic Trough Collectors", Renewable and Sustainable Energy Reviews, Vol. 77, pp. 1363-1374, 2017.

[43] X. Gao, Z. Su, "Active Disturbance Rejection Control for a Parabolic Trough Solar Field", 2021 4th International Conference on Control and Computer Vision, pp. 159-164, 2021.

[44] A. J., Sánchez del Pozo Fernández, A. J., Gallego Len, J. M., Escaño González, E. F. Camacho, "Hierarchical Set-point Optimization and Feedforward Strategy for Collector Defocusing of a Solar Plant", Solar Energy, Vol. 220, pp. 282-294, 2021.

[45] J. Sui, X. Ling, X. Xiang, G. Zhang, X. Zhang, "Transformer Oil Temperature Prediction Based on Long and Short-term Memory Networks", 2021 IEEE International Conference on Big Data (Big Data), pp. 6029-6031, 2021.

[46] C. Brosilow, B. Joseph, "Techniques of Model-based Control", Prentice Hall Professional, 2002.

[47] R. Carmona, "Analysis, Modeling and Control of a Distributed Solar Collector Field with a One-Axis Tracking System", Spanish, University of Seville, Spain, 1985.

[48] C. M. Cirre, L. Valenzuela, M. Berenguel, E. F. Camacho, "Control of Solar Plants with Automatic Set-point Computation", RIAI: Revista Iberoamericana de Automática e Informática Industrial, Vol. 1 pp. 56-66, 2004.

[49] C. Ionescu, B. Wyns, M. Sbarciog, L. Boullart, R. De Keyser, "Comparison between Physical Modeling and Neural Network Modeling of a Solar Power Plant", Proceeding of the IASTED International Conference on Applied Simulation and Modeling ASM, Vol. 4, pp. 28-30, 2004.

[50] M. Arahal, M. Berenguel, E. F. Camacho, "Comparison of RBF Algorithms for Output Temperature Prediction of a Solar Plant", Proceeding of CONTROLO, Vol. 98, pp. 9-11, 1998.

[51] M. Karamali, M. Khodabandeh, "A Distributed Solar Collector Field Temperature Profile Control and Estimation Using Inlet Oil Temperature and Radiation Estimates based on Iterative Extended Kalman Filter", Renewable Energy, Vol. 101, pp. 144-155, 2017.

[52] M. Z., Mohi Abadi, S. M. H., Mohammadi, S. A. A. Safavi, S. V. Naghavi, "On the Control of the Collector Field Outlet Temperature of Shiraz 250 KW Solar Power Plant", Applied Mechanics and Materials, Vol. 260, pp. 163-168, Trans Tech Publications Ltd., 2013.

[53] A. Kenary, M. Yaghoubi, F. Doroodgar, "Experimental and Numerical Studies of a Solar Parabolic Trough Collector of 250 kW Pilot Solar Power Plant in Iran", Sharjeh Solar Energy Conference, Sharjeh UAE, pp. 19-22, 2001.

[54] M. Yaghoubi, K. Azizian, A. Kenary, "Simulation of Shiraz Solar Power Plant for Optimal Assessment", Renewable Energy, Vol. 28, No. 12, pp. 1985-1998, 2003.

[55] M. Yaghoubi, K. Azizian, M. Salim Shirazy, P. Kanan, "Shiraz Solar Power Plant Simulation with Variable Heat Exchanger Performance", ASME 7th Biennial Conference on Engineering Systems Design and Analysis, American Society of Mechanical Engineers, 2004.

[56] O. Mahian, A. Kianifar, S. A. Kalogirou, I. Pop, S. Wongwises, "A Review of the Applications of Nanofluids in Solar Energy", International Journal of Heat and Mass Transfer, Vol. 57. No. 2, pp. 582-594, 2013.