Automatic control of a heat exchanger in a nuclear power station :

The classical and the fuzzy methods

C. Mendil*
Laboratory of Applied Automatic,
dept. of Automation,
University M'hamed Bougara
Boumerdes Algeria
*c.mendil@univ-boumerdes.dz

M. Kidouche
Laboratory of Applied Automatic
dept. of Automation,
University M'hamed Bougara
Boumerdes, Algeria
kidouche_m@hotmail.com

M. Z. Doghmane
Laboratory of Applied Automatic
dept. of Automation,
University M'hamed Bougara
Boumerdes, Algeria
doghmane_m@yahoo.com

***Abstract*—Without electricity everyday life would be difficult to be envisaged, it is therefore necessary to know how to produce it effectively and continuously. To meet the growing consumption of electricity, it was crucial to build factories capable of producing electricity with huge capacities. In recent years, nuclear techniques have undergone considerable development, characterized by the implementation of multiple disciplines. Wherein, automation has taken an important part of these developments. Driving the industrial equipment in safety mode, treating the information with many variables and actions' adjustment, can be ensured by analogical/digital automatic systems. This paper highlights control techniques of heat exchanger in a nuclear power station with disturbance compensation systems. Moreover, the fuzzy technique has been proposed to derive the control system. The main objective of this manuscript is to determine a prototype control model for an intelligent heat exchanger in a nuclear power reactor. Experimental data of BRENILLIS power plant has been used for the identification and modeling of the reactor. Furthermore, the transfer functions developed by the C.S.F and "Electricité de France" have been considered for the purpose of automating the nuclear power station.**

Keywords*—Nuclear power plant; intelligent heat exchanger; fuzzy driving techniques; identification and modeling; BRENNILIS power plant

I. Introduction

To study, design and control dynamic systems, it is advisable to model them mathematically on the basis of the laws of physics describing the phenomena involved (mechanical, electrical, thermal, magnetism…etc.)[1-2]. Some technical processes obey more complex laws described by similar derivative equations, whose resolution is not simple. For our study, the equations of the exchanger have been formulated, the parameters (resistance to fouling, coefficient of global exchange, wall temperature ...) of these dynamic equations are unknown and difficult to estimate because of the danger that exists in nuclear reactors [3-4], we do not arrive at the elucidated ones to highlight them in simulation testing approaches, we focused on index tests realized in France. The theoretical determination of the mathematical model of a heat exchanger is a laborious task, because it involves systems of differential equations difficult to solve. To this end, a fuzzy logic analysis [5-6] that took into account both the knowledge of a human expert and the uncertainty and inaccuracy of the data processed by the controller has been performed [7-8]. In our study, the use of fuzzy logic whose satisfactory result (no overshoot and response time are significantly improved) are compared to a dynamic analysis by the classical method.

II. Nuclear power plant

Nuclear power plant is a power generator that uses one or more nuclear reactors; it is composed of many parts as shown in Fig. 1, in this study we are interested in the heat exchanger [9-10].

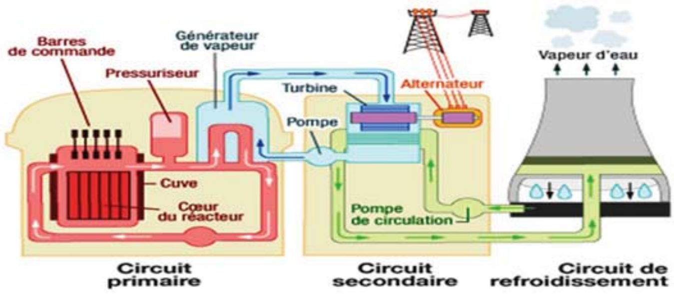

Fig.1. Schematic diagram of typical Nuclear power plant

III. Mathematical model of heat exchanger

In this part, the mathematical model based on mass energy transfers functions that take place in a nuclear heat exchanger has been given, where the transfer functions for steam flow equation is:

$$Q_v = Q_{v0}\left(\frac{v_a P}{P_0} + b v_c\right) \tag{1}$$

The power equation is:

$$W_T = W_{T0}\frac{Q_{vT}}{Q_{v0}} \tag{2}$$

Where Q_v is steam flow, Q_{v0} is the initial steam flow, v_a is the opening fraction of the turbine inlet valve, v_c is the opening fraction of the valve at the turbine bypass, P is the pressure, P_0 is the initial pressure, b being the fraction of steam flow admitted by the turbine bypass. W_T is the power

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provided by the turbine, W_{T0} is the power supplied by the turbine corresponding to the nominal flow Q_{V0} , and Q_{vT} is the flow of the steam admitted by the turbine. The dynamic parameters in (1) and (2) are unknown, and since we do not manage to elucidate them in order to be highlighted in the simulation tests, tests made by BRENNILLIS in France have been used [11]. The identification method used by BRENNILLIS researchers is based on *Strejc* approach [12].

A. Combined Automatic rejection Control System (ARS)

In practice, to mitigate the effects of major dangerous disturbances, a combined ARS shown in Fig. 2 is used [12]. Transfer function of the compensator is given by (3)

$$C_i(s) = -\frac{W_{Fi}(s)}{W_0(s)} \tag{3}$$

With W_0 is the transfer function of the main object, and W_{Fi} is the transfer function with respect to the perturbation. W_R is the transfer function of the regulator .

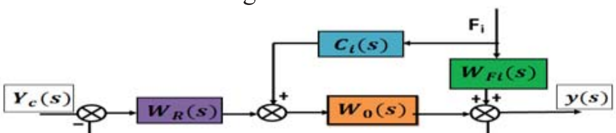


Fig.2. Scheme of heat exchanger transfer function with rejection compensator

B. The NASLIN Criterion

The parameters of the regulator are calculated using NASLIN criterion. These parameters are taken from NASLIN's reports, where

$$\frac{a_1^2}{a_0 a_2} \geq \alpha, , \frac{a_2^2}{a_1 a_3} \geq \alpha , \frac{a_3^2}{a_2 a_4} \geq \alpha , \cdots\cdots\cdots , \frac{a_{n-1}^2}{a_{n-2} a_n} \geq \alpha \tag{4}$$

With $\alpha = \frac{1}{2}\left[4.8 - \log(D\%)\right]$,

D is the maximum exceedance expressed as a percentage of the final value, and α is a constant that depends on the value of D% [11].

IV. DYNAMIC ANALYSIS OF CONTROL CHAINS

A. Pressure control chain

The block diagram of the pressure control chain is shown in Fig.3; the compensator transfer functions calculated for this control chain are given by (5) and (6).

- For 100% load

$$W_{C1} = \frac{0.19S + 0.0128}{165S + 1} \tag{5}$$

- For 50% load

$$W_{C1} = \frac{1.67S + 0.011}{270S + 1} ; W_{C2} = \frac{408S^2 + 27.2S}{4500S^2 + 460S + 1} ; \text{and}$$

$$W_{C3} = \frac{7.08S + 0.47}{140S + 1} \tag{6}$$

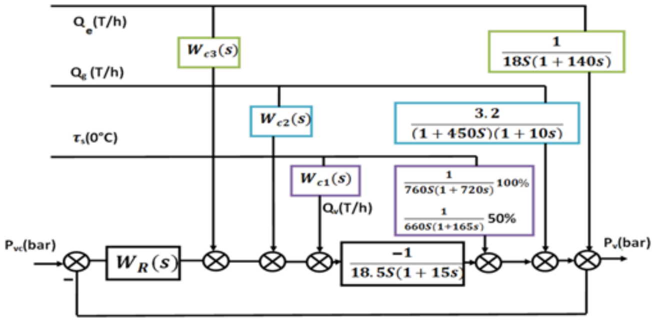
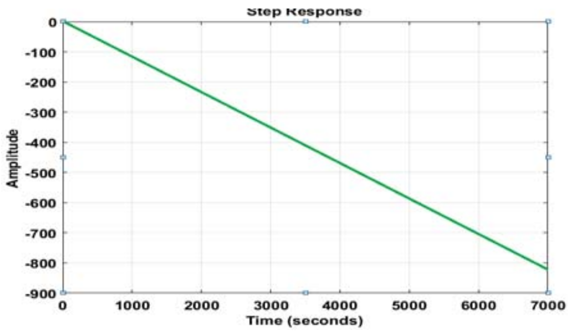


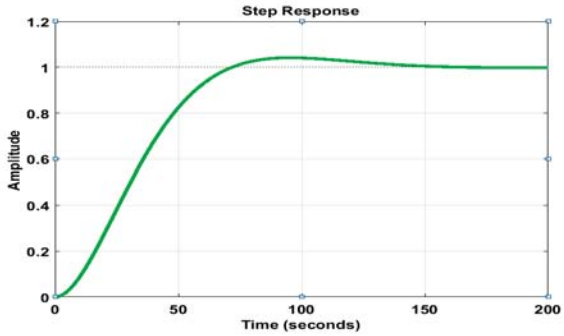
Fig. 3. Block diagram of the open loop system of pressure chain

Q_e is the water flow, τ_s is the temperature, and P_V is the steam pressure,P_{Vc} is the set point.

1) Pressure adjustment chain simulation



(a)



(b)

Fig. 4. Impulse response of the system: a) Open loop b) Closed loop

From Fig. 4(a), it is noticeable that the system is unstable because of the existence of a dominant integrating pole. To compensate its effect a proportional regulator has been added.

From Fig. 4(b), the closed-loop system with the regulator is stable and has improved performance: 60s response time and no static gap. The adjustment parameters of the proposed regulator are adequate [13]. The method used to calculate these parameters is based on the NASLIN criterion. Thus, the ratio of NASLIN is used, to obtain at the first exceedance of the 10% order a stabilized process within the tolerance tube. However, the first overshoot that was obtained is of the 5% order which do not have a third overtaking [14]. The process is stabilized after 60 seconds.

From Fig.5, we find that the index response of the system in closed loop with compensators is almost identical to that without disturbance, which means that the disturbances are effectively compensated.

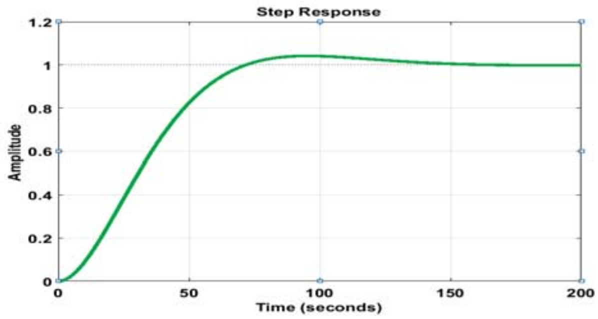
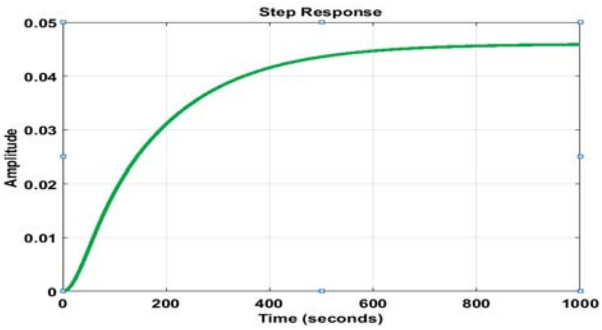
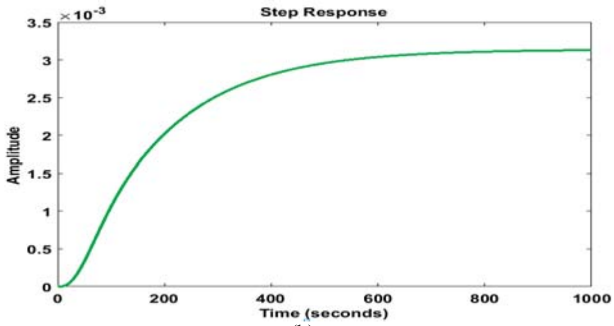


Fig.5. Impulse response of closed loop system with compensated disturbance

2) Influence of temperature disturbance τ_s on steam pressure Pv at 100% load



(a)



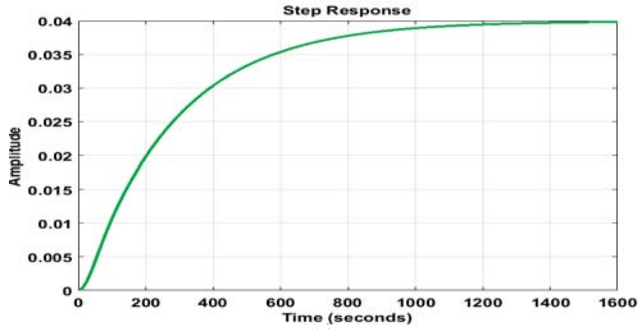
(b)

Fig.6. Closed loop response with disturbance level of the Temperature τ_s at 100% load: a) without Compensation, b) with compensation

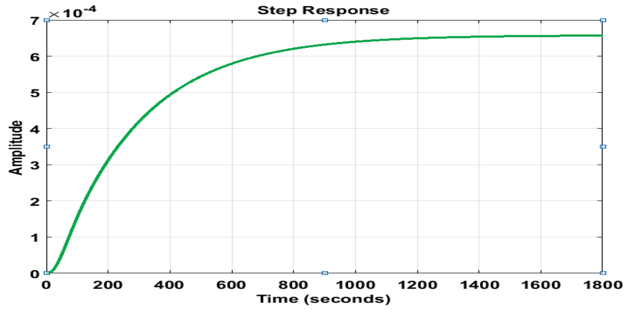
From Fig. 6 (a), we notice that the maximum variation of the pressure Pv is not negligible knowing that its value is of the order 0.0459 (bar).The variation of the pressure remains constant at t = 10 min [15]. From Fig. 6 (b); we can see that the maximum variation of the pressure is reduced to a negligible value of 3.13×10^{-3} (bar).

3) Influence of the temperature disturbance τ on the vapor pressure Pv at the 50%load

From Fig. 7 (a) it is noticeable that the variation of the pressure reaches a maximum value 0.0397 (bar), the effect of the disturbance is still low at the 50% operating load [16]. From Fig. 7.b, the maximum variation is reduced to a low value of 6.56×10^{-4} (bar).



(a)

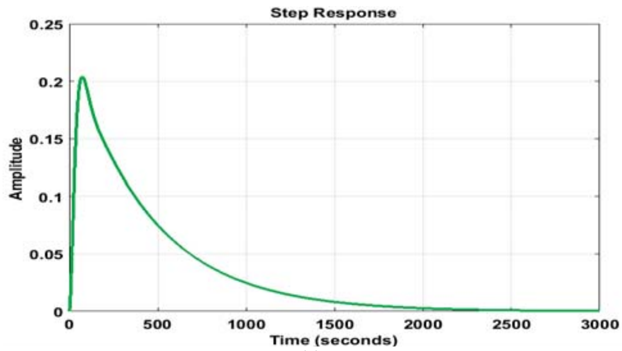


(b)

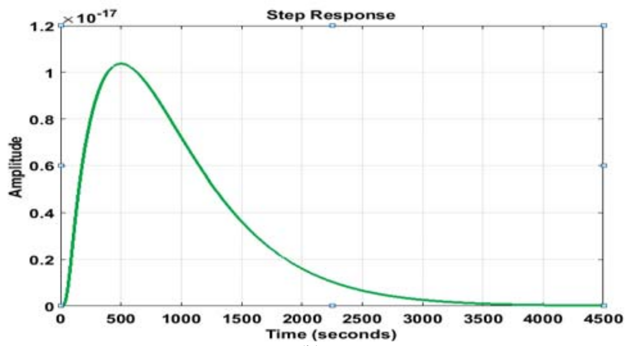
Fig.7. Closed loop response at a disturbance level of Temperature τs with 50%load: a) without compensation, b) with compensation

4) Influence of gas flow disturbance Q_g on vapor pressure Pv

From Fig. 8 (a) it is noticeable that the effect of the disturbance is not negligible; its maximum variation is of the order of 0.2 Bars. From Fig. 8 (b), the vapor pressure returns to zero, but the variation reaches a maximum value is almost zero, it is of the order of 1.04×10^{-17} (bar).



(a)

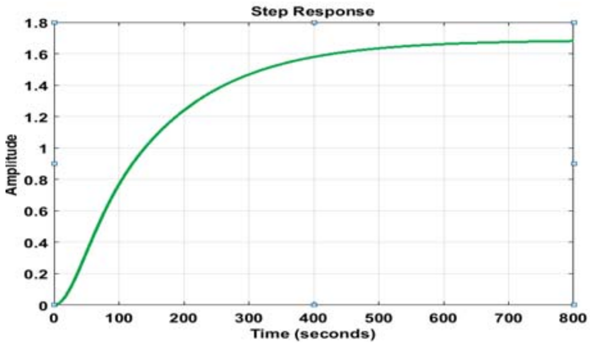


(b)

Fig.8. Closed loop response at a gas flow disturbance step Qg: a) without compensation, b) with compensation

5) Influence of the disturbance of the water flow Qe on the vapor pressure Pv

From Fig. 9 (a) we notice that the variation of the vapor pressure reaches a maximum value and which is important, it is of the order of 1.68 (bar). From Fig. 9 (b), the maximum variation of the vapor pressure at one step of the water flow and reduced to 7.9×10^{-3} (bar), which mean that the compensation is done efficiently [17].



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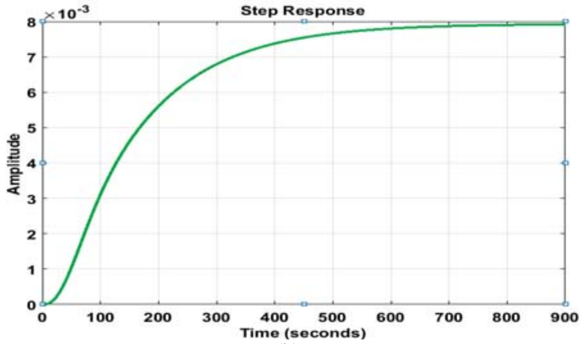


(b)

Fig.9. Closed loop response at a disturbance level in Water flow Qe: a) without compensation, b) with compensation

B. Temperature control chain

The block diagram of the temperature control chain is shown in Fig.10; the compensator transfer functions calculated for this control chain are given by (7).

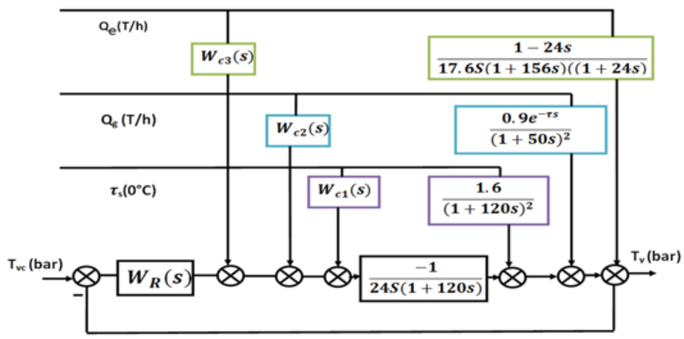


Fig. 10. Temperature control chain: operation of a priority reactor

$$W_{C1}(S)=\frac{38.4S}{120S+1},\ W_{C2}(S)=\frac{9072S^3+2516S^2+21.6S}{8750S^3+2850S^2+103.5S+1},$$

$$W_{C3}(S)=\frac{-35712S^3-96S+24}{65894S^2+3168S+17.6} \tag{7}$$

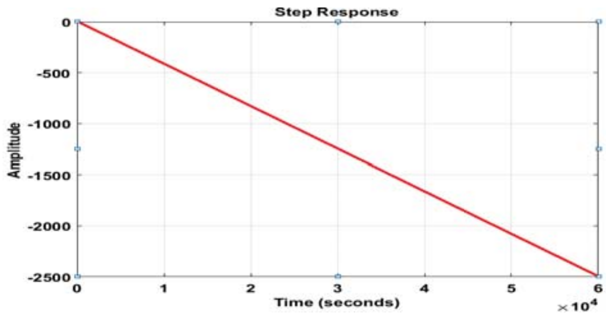
The regulator transfer function calculated by the NASLIN criterion for a 10% overflow and α = 2 is $W_R(S)=-0.1$

1) Results and discussions of simulations of the temperature control chain

Compared to the main results in open loop relating the driving parameter (Steam temperature) with respect to the closed loop with addition of a P-action regulator, Fig. 11(a) and (b) illustrates the evolution profile of the P_V temperature with and without the presence of disturbances.

From Fig. 11(a); we find that the system is unstable because of the existence of a non-minimal phase shift pole, which influences the stability of our system [18]. The action of the adding the proportional regulator is dedicated for this purpose. From Fig. 11(b), the response time is minimal for a damping factor ε = 0.7 because it is beyond this value while the first overrun is at 5%.

From Fig.12; the impulse response of the closed loop system with compensator is almost identical to that without disturbance.



(a)

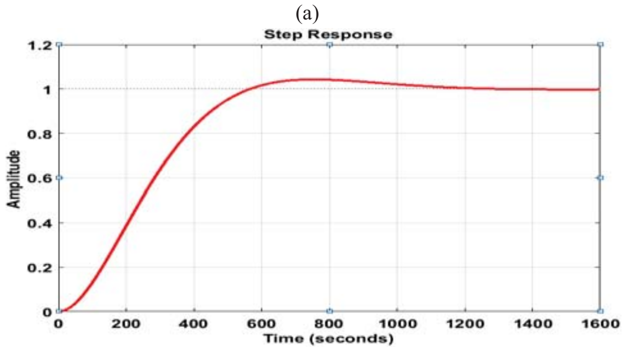


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Fig. 11. Impulse response of temperature chain without compensation; a) open loop, b) Closed loop

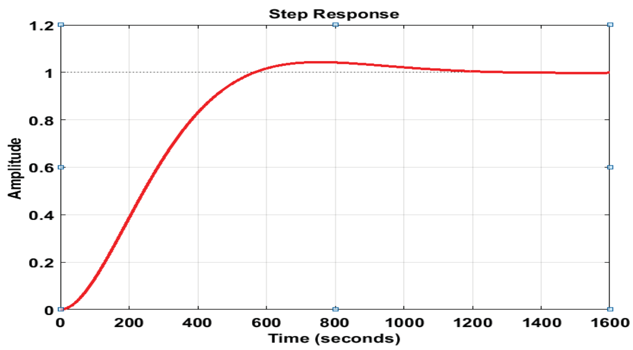
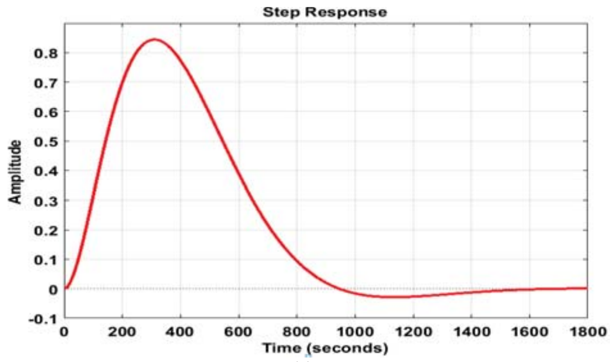


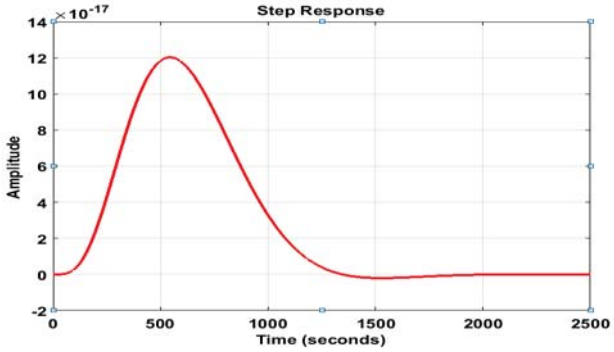
Fig.12. Closed loop response of temperature chain with compensated disturbance

2) Influence of the temperature perturbation τ_s on the vapor temperature at 100% load

From Fig. 13 (a); we found a maximum variation of 0.842 (°C). The disturbance was canceled at the 1600 (s), this time is important and can be annoying. For Fig. 13 (b); this figure shows us that the maximum variation of $12\times10^{-17}$is almost zero which validates the computation of the compensator found early in this manuscript.



(a)

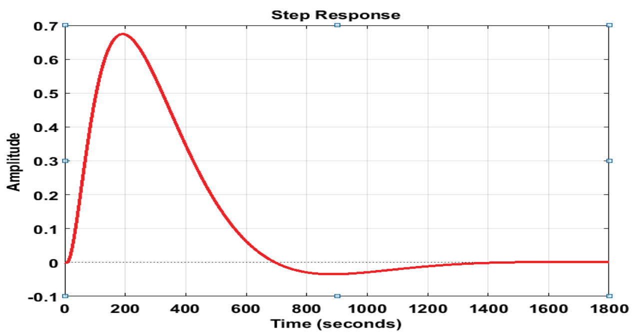


(b)

Fig.13. Closed loop response of temperature chain: a) without compensated disturbance, b) with compensated disturbance

3) The influence of gas flow disturbance on the vapor temperature

From Fig. 14 (a); the disturbance is slightly important, the variation of its maximum amplitude is of the order of 0.673 (°C) which tends to be cancelled after a very high time of 10 min. From Fig. 14 (b); a compensator was used to cancel this negative effect with an overshoot of ± 0.03 over a time of about 2 min. we can conclude that the compensator is working successfully.



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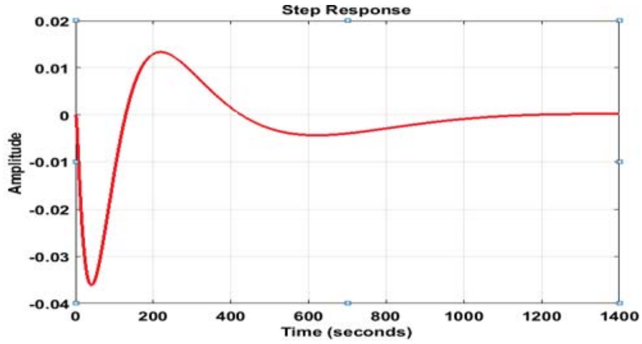
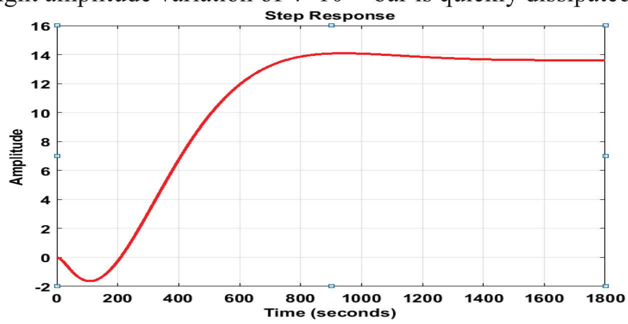


(b)

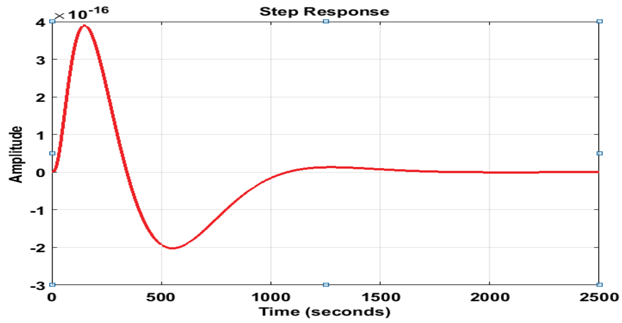
Fig.14. Closed loop response at a disturbance level of the Gas Flow: a) without compensation, b) with compensation

4) Influence of the disturbance of the effect of the steam flow on the vapor temperature

From Fig. 15(a); we found that the maximum variation is very high, it is of the 14 (C°) orders, and the temperature remains constant for this value, the time is 800s. From Fig. 15 (b); after compensating this disturbance it became zero, however a very slight amplitude variation of 4×10^{-16} bar is quickly dissipated



(a)

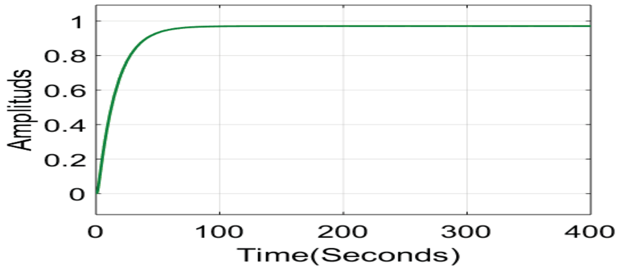


(b)

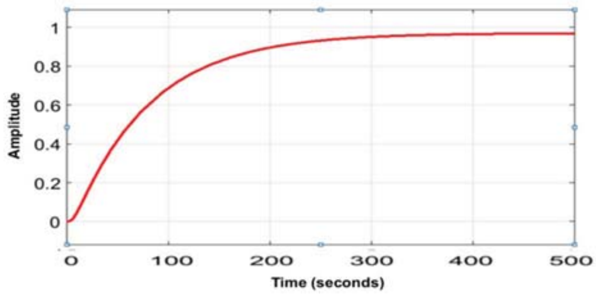
Fig. 15. Closed loop system response at a disturbance level Water flow a) without compensation, b) With compensation.

V. SIMULATION OF FUZZY LOGIC CONTROL CHAIN

For the control of the two supposed independent variables Pv and Tv, two fuzzy controllers were designed. This being said, separately for each of them, it has two inputs namely, the error and the variation of the error, and also the variation of the control variable actions has been defined. For the membership functions, a set of three quantifiers with the form "trapmf" and "gbellmf" has been used. For the defuzzification module, the average maximum method has been used. For the realization of the inference engine, the MAMDANI method has been considered.



(a)



(b)

Fig.16. Fuzzy logic heat exchange model: **a)** Closed loop response of pressure chain, b**)** closed loop response of temperature chain

From Fig. 16 (a), it is remarkable that the system performance is significantly improved with a total absence of an overrun; the improved response time is of the order of 60 s. From Fig. 16 (b), the good performance of this fuzzy correction is also noticeable, the fuzzy corrector allowed to obtain a faster system without any overruns [19].

In conventional driving, the defined and calculated adjustment parameters are good, knowing that the static and residual deviations are eliminated but with an important response time [20]. In fuzzy driving system, the heat exchange quickly stabilized, with much better performance.

VI. Conclusion

As it was assigned in this study, a comparison between the automatic conduct of a heat exchanger of a nuclear power plant has been given by two methods; classic method and Fuzzy logic expert method. Regulating the facilities of a nuclear power plant is not easy; it includes very complex process and requires refined interpretations of automatic driving. On the simulation of the so-called analogue automatic control; it was carried out on two independently processed parameters, namely the setting of the vapor pressure, in addition to the adjustment of the vapor temperature. The simulation results of these two main parameters (without compensation) are illustrated, where for the setting of the pressure and the steam temperature, the system is unstable. As a result, the adjustment parameters are identified, calculated and displayed using the action controllers, the system becomes stable again. The simulation results of these two main parameters (with disturbance compensation) are realized. The main disturbances taken into account for the regulation of the two main parameters are flow of carbon dioxide, water flow, steam flow, carbon dioxide temperature.

Fuzzy expert system operation is clearly superior to analog autopilot. The perfect knowledge of the thermal process of the object, by taking into account the multiple connection of the driving parameters (incoming and outgoing), and taking into account the disturbances, made it possible to refine the quality of regulation by the fuzzy logic in order to optimize the performance of this system.

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