Design of optimal fuzzy controller for water level of U-Tube steam generator in nuclear power station

Hamdi. M. Mousa*, Magdy. A. Koutb**, Sayed. M. El-Araby***, And Elsayed. H. M. Ali***

*Faculty of Computers and Information, Menoufia University, Egypt
** Industrial electronics and control department, Faculty of electronic engineering, Menoufia University, Egypt
***Engineering and scientific instruments department, nuclear research center, Atomic energy authority, Cairo, Egypt
sayedmahdy@yahoo.com

Abstract: The steam generator is a highly complex, nonlinear and time-varying system and its parameters vary with operating conditions. A method to improve the performance of nuclear steam generator in nuclear power station is introduced. Combination of genetic algorithm technique and fuzzy logic control is carried out. The optimal parameters of fuzzy logic controller are achieved. These parameters include; the membership functions of water level error and changes water level error, the rule base, and the input scaling gains. Steam generator model implemented using MATLAB/SIMULINK. The optimal controller was applied to control the water level of nuclear steam generator and it's compared with conventional controller. Simulation results indicate that the optimal fuzzy controller greatly improves the performance of nuclear steam generator. Moreover the proposed controller is robust to any disturbance related to sudden changes in steam flow rate and water level. Moreover the proposed controller is robust to any disturbance related to load variations.

[Hamdi. M. Mousa, Magdy. A. Koutb, Sayed. M. El-Araby, And Elsayed. H. M. Ali. **Design of optimal fuzzy controller for water level of U-Tube steam generator in nuclear power station.** Journal of American Science 2011;7(4):629-637]. (ISSN: 1545-1003). http://www.americanscience.org.

Keywords: Fuzzy logic control, genetic algorithm, steam generator, nuclear power stations.

1. Introduction

Due to growing electricity demands, many countries are investing in nuclear power stations. During the operation of the nuclear power station, different changes in the operating conditions may occur such as water level in steam generator. Steam generator is a very important component of nuclear plant. It is of significance for nuclear reactor normal operation to maintain it work safely and reliably. For the steam generator in a nuclear power station, the main goal of its control system is to maintain the steam generator water level at a desired value [1]. The water level of a nuclear steam generator is of great importance in order to secure the sufficient cooling water for removing the primary heat and to prevent the damage of turbine blades [2]. The water level control problem of steam generator has been a main cause of unexpected shutdowns of nuclear power plants. In France, nuclear energy provides about 80% of the whole electricity production. This production must be able to vary proportionally to the consumption [3]. Figure 1 shows the steam generator (SG) in a nuclear power station [4].

It is very important to keep the operation of nuclear power station in highly safe mode. Therefore, an intelligent control system is required to compensate the steam flow rate changes produced sudden changes in load variations in the operating condition of the nuclear power station.

The conventional proportional– Integral (PI) controller [5] was used to control the water level of the nuclear power stations. Simulation results show that conventional PI controller has long time delay between actual water level and reference level, big value of overshoot and undershoot, and bad tracking. Fuzzy Logic Control (FLC) is one approach of the Artificial Intelligence (AI) techniques that is used to control the performance of nuclear power stations [6],[7]. Simulation results show that the output response is improved, but it still insufficient to get an optimum response. The rule -base of fuzzy logic controller reflects the human expert knowledge, expressed as linguistic variables, while the membership functions represent expert interpretation of those same variables. In the absence of such knowledge, trial and error is a common approach used to optimize these fuzzy logic controller parameters, with respect to the performance of the system for each Knowledge base formulated [8]. This approach becomes impractical and not accurate for adjusting the parameters of membership function and rule base of nonlinear systems.

In this paper a genetic algorithm is proposed for optimal tuning parameters of fuzzy controller namely, rule base, membership function, and input scaling gains. The proposed genetic fuzzy controllers greatly improves the output response of the nuclear power station and dramatically decreases the overshoot and undershoot, the steady state error close to zero value, decreases the settling time and rise time. The paper organized as follows: Section one describe the mathematical model of nuclear steam generator.

Section two gives verification of the water-level behavior for the UTSG

Section three gives the design of water level controller for UTSG. Section four gives results and discussion, and final section is the conclusions.

1. Mathematical Model of U- Tube Steam Generator (UTSG)

A steam generator shows complicated dynamic behaviors with nonlinear characteristics. Some theoretical models based on the thermodynamic experiments and/or energy conservative equations have been developed to use for operator training simulator and accident analyses and so on. However, these are inadequate as mathematical models for designing controllers due to complexities. In this paper the Irving's steam generator model [9] has been used described in equation 1 which has been widely used for control purposes. The Irving's model is a linear parameter varying model of which parameters depends on reactor power level, listed in Table 1.

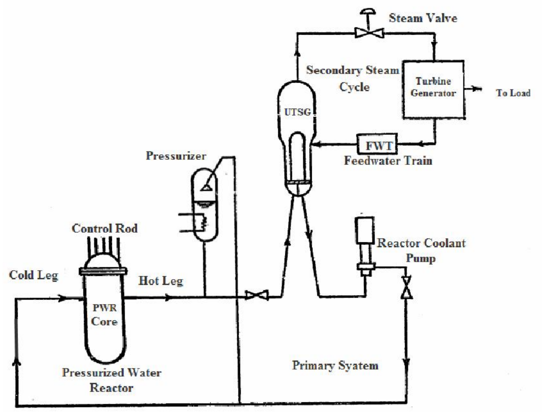

Fig. 1 Layout of steam generator (SG) in a nuclear power station

1.1. UTSG dynamics

The simulation model was developed using the Simulink [10] utility due to its friendly user interface and high flexibility environment [11] as shown in Figure1. The following parts describe the simulation of UTSG model which can be divided to the following necessary parts:

a. Water level output of UTSG.
b. Mass capacity effect of the UTSG.
c. Thermal negative effect caused by “swell and shrink”.
d. Mechanical oscillation effect caused by the inflow of the feed-water to the UTSG.

The Irving's model is a linear parameter varying model of which parameters depends on nuclear reactor power level, listed in table 1. The simulation model was developed using the SIMULINK [10] utility due to its friendly user. A top view of SG model implemented in Simulink is shown at Figure 2.

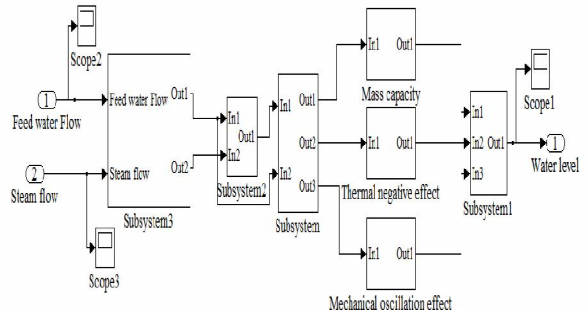

Fig. 2. A Top view of steam generator model implemented in Simulink

The water level of UTSG is given by the following equation:

$$y(s)=\frac{G_1}{s}\left(Q_w(s)-Q_s(s)\right)-\frac{G_2}{t_2 s+1}\left(Q_w(s)-Q_s(s)\right)+\frac{G_3 s}{s^2+2t_1^{-1}s+t_1^{-2}+4p^2T^{-2}}Q_w(s) \tag{1}$$

Where: $y(s)$ is water level of steam generator, $Q_w(s)$ is feed-water flow-rate, $Q_s(s)$ steam flow rate, T is oscillation period, and τ_1 , τ_2 are damping time constants. G_1/s is the mass capacity effect of the UTSG. It integrates the flow difference to calculate the change in water level. This term accounts for the level change due to feed water inlet to steam generator and the steam outlet from it. This quantity means the actual water capacity which critically affects the removal capability of the primary heat. G1 is a positive constant and does not depend on load.

$G_2/(\tau_2 s+1)$ is the thermal negative effect caused by “swell and shrink”. Since these phenomena exhibit exponential responses for step changes of the feed water flow-rate and the steam flow-rate, they are described by a first-order equation. G2 is positive and dependent on load. As load increases G2 decreases.

$\left[G_3 s/\left(s^2+2t_1^{-1}s+t_1^{-2}+4p^2T^{-2}\right)\right]Q_w(s)$ is the mechanical oscillation effect caused by the inflow of the feed-water to the UTSG.

This is a mechanical oscillation term due to momentum of the water in the downcomer. All the water removed from the steam is returned to the downcomer and is recalculated. The recalculating water has large momentum acting against relatively small flow-rate changes. When the feed-water flow-rate is suddenly decreased, the water level in the downcomer falls initially and then begins to oscillate. This is due to the momentum of the water in the downcomer keeping the recalculating flow going down initially and then slowing down. The mechanical oscillation disappears completely after a small multiple of the damping time constant. The variable G3 is positive. The dynamics of nuclear steam generator model can be described by the following state-space equations:

$$\frac{dx}{dt} = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) \qquad (2)$$

Where $x(t) = [x_1(t), x_2(t), x_3(t), x_4(t), x_5(t)]^T$ is the state vector, $u(t)$ is the control input, $y(t)$ is the output, and A, B, C are defined in (3)

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & G_1 \\ 0 & \frac{-1}{\tau_2} & 0 & 0 & \frac{-G2}{\tau_2} \\ 0 & 0 & \frac{-2}{\tau 1} & 1 & G3 \\ 0 & 0 & -(\tau_1^{-2} + 4\pi^2 \mathrm{T}^{-2}) & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad C = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}^T \qquad (3)$$

The model parameters at different powers have been identified [9] from experimental data and are given in Table 1.

Table (1): Steam generator dynamic parameter according to operating power

Power %	τ_1	τ_2	T	G1	G2	G3	Q_{ST} (kg/s)
5%	41.9	48.4	119.6	0.058	9.63	0.181	57.4
15%	26.3	21.5	60.5	0.058	4.46	0.226	180.8
30%	43.4	4.5	17.7	0.058	1.83	0.310	381.7
50%	34.8	3.6	14.2	0.058	1.05	0.215	660
100%	28.6	3.4	11.7	0.058	0.47	0.105	1435

2- Verification of the Water-Level Behavior for UTSG

The transient behavior of the water level is dominated by the thermodynamics of the two-phase mixture in a steam generator and exhibits an inverse response behavior, which is the so-called "swell and shrink" phenomenon. As the steam flow rate increases, the pressure on the steam dome region of the steam generator decreases and the two phase flow mixture expands and shows an increase in the water level (swell). On the other hand, as the feed-water flow rate is increased, the steam bubbles in the two phase flow mixture collapse showing a decrease in the water level (shrink). These two effects are more severe especially at low operating powers and cause difficulty in an effective controller design for the UTSG. The numerical simulation for verifying the "swell and shrink" behavior is done as by simulating the Transient responses of the narrow range water level of SG at different operating powers (5%, 15%, 30%, 50% and 100% full power) due to step increase in feedwater flow -rate. And Transient responses of the narrow range water level of SG at the same different operating powers due to step increase in the steam flow-rate. Figure 3 and figure 4 shows the responses of steam generator water level to step changes in feedwater and steam flow rates at different operating powers respectively.

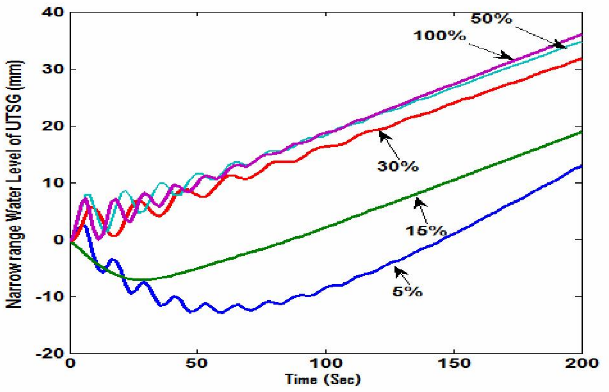

Fig. 3 Responses of SG water level at different operating powers to a step in feed-water flow rate

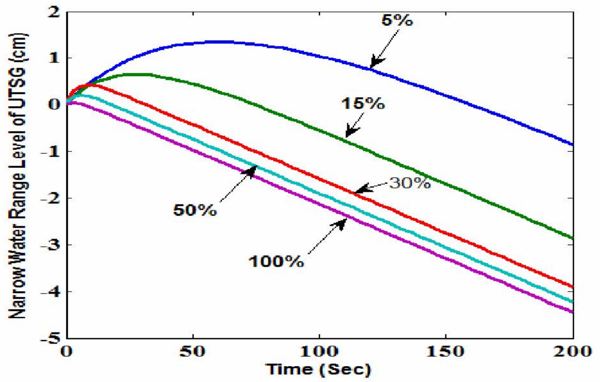

Fig. 4 Responses of SG water level at different operating powers to a step in steam flow rate.

3-Design of water level controller for UTSG

The command to the controlled system is the desired water level of the SG. A PI controller is chosen as a conventional controller. There are number of design requirements where established, based on step time response; reducing overshoot oscillation, and settling time, quick response good disturbance rejection.

3.1 Conventional controller

A Proportional-Integral controller or PI is a standard feedback loop component in industrial control applications. It measures an "output" of a process and controls an "input", with a goal of maintaining the output at a target value, which is called the ”set point”. For conventional control of SG, PI controller was used [12].

$$U_{level}(t) = K_{pl}(t) + K_{il}(t)\int_{0}^{t} e_l(t)dt \qquad (4)$$

Where $U_{level}(t)$ is level control signal, , $e_l(t)$ is level error signal (mm) and its is equal the difference between level set point and actual level of UTSG, and K_{pl} , K_{il} ,are the proportional and integral gains of level controller respectively.

3.2 Fuzzy logic controller

Fuzzy logic control is based on the principles of fuzzy logic developed by Zadeh in 1965. It is a non-linear control method, which attempts to apply the expert knowledge to design the required controller. Based on the operator experience, structure of UTSG and flow diagram of water and steam inside the steam generator, the proposed structure of the fuzzy controller has two inputs and one output. These inputs of UTSG are water level error (WLE) and the rate of change in water level error (CWLE) respectively. Figure 5 shows the initial membership functions of the fuzzy controller. Five triangular membership functions for two inputs and one output, the linguistic terms for defining the membership functions are: NB is negative big, NS is negative small, ZE is zero, PS is positive small, and PB is positive big. Initial 25-rule base of fuzzy logic controller is shown in Table 2.

Table (2) Initial fuzzy rules of fuzzy controller

		Water Level error				
		NB	NS	ZE	PS	PB
Change in water level error	NB	NB	NB	NB	NS	ZE
	NS	NB	NS	NS	ZE	PS
	ZE	NB	NS	ZE	PS	PB
	PS	NS	ZE	PS	PS	PS
	PB	ZE	PS	PB	PB	PB

Once the membership functions and the rule-base of the fuzzy logic controller are determined, the next problem related to its implementation is the issue of tuning, which remains a more difficult and sophisticated procedure since there is no general method for tuning the fuzzy logic controller [13],[14] and [15]. Moreover the fuzzy control method has some limitations from the fact that its performance largely depends on initial membership function parameters and how to settle a rule base [16]. So, the Genetic Algorithm is applied to optimize parameters of fuzzy logic controller and input scaling gains.

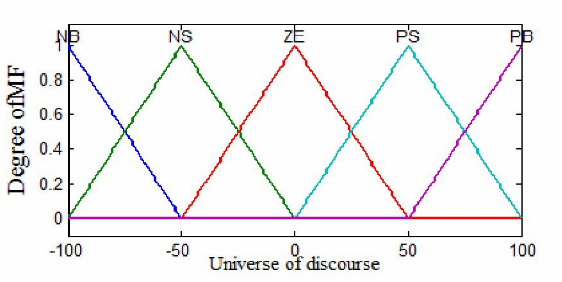

Fig. 5. Membership of function of fuzzy controller

3.3 Genetic fuzzy controller design

The optimal fuzzy controller is a fuzzy logic controller that is tuned off-line by the GA [17],[18] . To design the optimal fuzzy controller, the genetic algorithms are applied to search the globally optimal parameters of the fuzzy logic, and the Pittsburgh approach [19] is used to reduce the required chromosome length that represents the different component of fuzzy logic controller. A number of assumptions ‘that were made in respect of the fuzzy logic controller to be optimized’ are discussed in the following:

3.3.1 Decoding fuzzy logic using GA chromosome

The primary assumption for the design of OFC is a symmetrical system; a corresponding fuzzy logic controller would also exhibit symmetry about the set point in respect of its membership functions and rule base. This assumption was exploited in order to attempt to reduce the number of bits required to define the fuzzy logic controller for genetic algorithm optimization.

3.3.2 Genetic tuning of rule-base

Genetic tuning of rule base assumes a predefined set of fuzzy membership functions in the data base. A total of 9-bits in chromosome are used to extract rule base consistent with the following assumptions;

1- The magnitude of the output control action is consistent with the magnitude of the input values, mid-range input values in mid-range output values, and small/zero input values in small/zero output values.
2- If a large negative (positive) input generates a large negative (positive) response, then it is likely that slightly smaller, negative (positive) inputs will necessitate a response of like polarity, but smaller magnitude, and so forth until a zero-crossover point is reached at which point the polarity of the response changes[20],[21].

3.3.3 Tuning membership functions

To encode the fuzzy logic controller membership functions associated with the two inputs and one output, a number of assumptions are made in respect of the distribution of fuzzy sets across the universe of discourse (UOD) for each fuzzy variable of fuzzy controller. These assumptions are;

1-The UOD is symmetrical about the central, zero regions for each variable.

2-The inner and central UOD-range membership functions could assume either triangular membership function, or trapezoidal membership function, shapes only[22],[23],[24].

3-The number of fuzzy sets for the controller was fixed at five (NB, NS, ZE, PS, PB).

The evaluated fuzzy logic controller contains three variables, WLE, CWLE as input variables and output as control-action. Seven bits for each variable are used to define the properties of the membership functions to be optimized. For each variable, their respective seven bits of GA-chromosome segments are sub-divided into two fields:

(a) The offset field. Three bits are used to effect change of shape to the membership functions from triangular to trapezoidal of varying widths and positions. In addition the algorithm uses the offset value to ensure the following constraints are observed by every evaluated fuzzy logic controller. A 50% overlap is maintained between adjacent membership functions.

(b) The expansion and compression factor field. Four bits are used to affect expansion/compression of the membership functions.

3.3.4. Decoding fuzzy logic controller scaling gains

The GA is used to optimize two fields, WLE-scaling and CWLE-scaling, are included in the GA –chromosome. Each consisting of 7- bits, which are decoded to yield values of gain for the appropriate gain blocks of the fuzzy logic controller.

3.3.5. GA objective function

The convergence of the genetic algorithm to a feasible solution depends upon some objective measure of each potential fuzzy logic controller performance; the target of the control is the minimization of the error. In this work the genetic algorithm is driven by the minimization of the mean square error as illustrated in equation 5, [25],[26].

$$F(x) = \frac{1}{N}\sum_{k=1}^{N}\left(y(k) - y_{ref}(k)\right)^{2} \qquad (5)$$

Where F(x) is the fitness function, y(k) is the actual water level of steam generator simulation model in correspondence of the parameters proposed by a chromosome, $y_{ref}(k)$ is the desired reference trajectory of water level, and N is the number of time steps in which the mission time is divided. During the search, an archive of the best solutions found in the successive generations is kept updated.

In order to design the OFC, we define some simulative parameter of genetic algorithm as follows, algorithm used double -point crossover, crossover rate is 0.65, mutation rate is 0.003, proportional fitness assignment binary chromosomes (gray decoding) and non-overlapping population updates, a population size is 30, chromosome length is 44. Finally the solution of the final optimization problem is achieved using the Genetic Algorithm Toolbox for MATLAB [27], and has been utilized to carry out the automatic optimization of fuzzy controller [28].

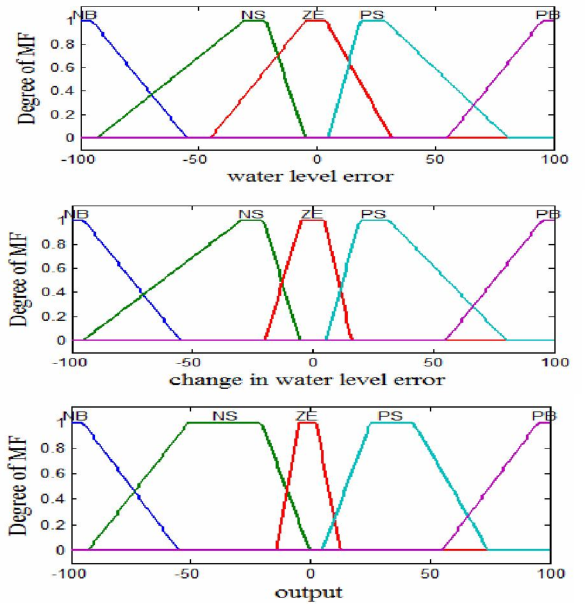

Fig. 6. Optimized MF of Fuzzy Controller

4-Results and discussion

For all simulations of the designed controller, the optimal fuzzy controller was tuned off-line. After running the GA, it gives the optimal fuzzy controller parameters as following; proportional scaling gain is 0.992, derivative scaling gain is 5.91811, the optimal solution at GA-chromosome is 001100001101110011001010110001101110101101110, the optimized MF for two inputs and output of fuzzy controller is shown in Figure 6, and the optimized fuzzy inference rules are listed in Table 4.

Several tests are implemented to validate the efficiency of the designed optimal fuzzy controller. In our simulation, at 5% of full power of nuclear power station the water level is step increased from zero level 150 mm at instant 200 second, then at time 1500 second the water level is subjected to sudden change in steam flow rate as disturbance increased from zero level to 28.4 kilogram per second (kg/s).

Table 3. The optimized fuzzy rules

		Water Level error				
		NB	NS	ZE	PS	PB
Change in water level	NB	NB	NB	NB	NS	ZE
	NS	NB	NB	NS	ZE	PB
	ZE	NB	NS	ZE	PS	PB
	PS	NB	ZE	PS	PB	PB
	PB	ZE	PS	PB	PB	PB

5-Conclusion

This paper focuses on the level control of a steam generator in a nuclear power station. It is very difficult to effectively control the water level of nuclear steam generator, because swelling and shrinking caused by many kinds of disturbances, such as a feed water flow rate, feed water temperature, main stream flow rate, and coolant temperature. Control of UTSG water level strongly affects nuclear power station availability. There has been a special interest in this problem during low power transients because of the dominant thermal dynamic effects known as shrink and swell. Also, the non-minimum phase property, changing parameter according to power level, make it difficult to control the water level of a steam generator. In this paper, Combination of genetic algorithm technique and fuzzy logic control was carried out. The optimal parameters of fuzzy logic controller are satisfied. These parameters include; the membership functions of water level error and changes water level error, the rule base, and the input scaling gains. The main advantage of the proposed controller is capability to deal with sudden changes in water level variation due to steam flow rate changes, hence it reduces impulses appears in feed water flow rate. So we can say also that Simulation results indicate that the proposed controller greatly improves the performance of nuclear steam generator. Moreover the proposed controller is robust to any disturbance related to steam flow rate variations.

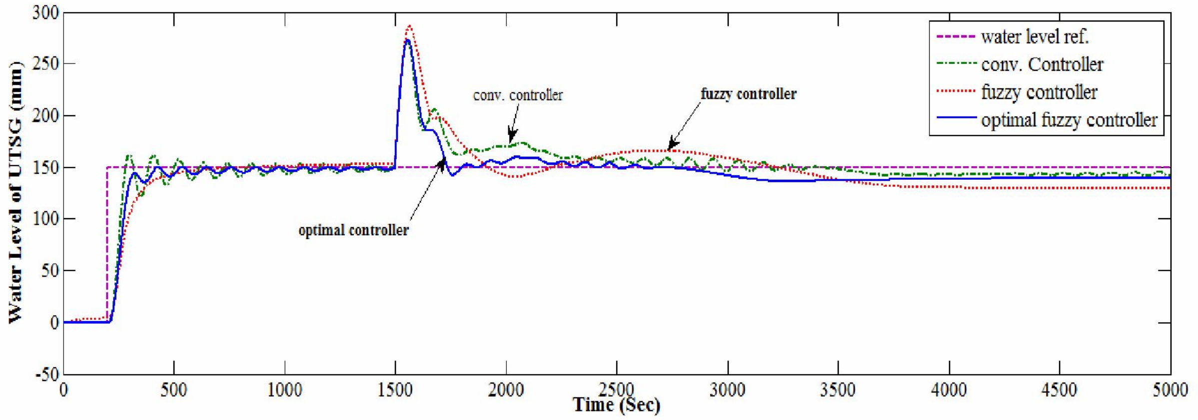

Fig.7 steam generator water level response for conventional and optimal fuzzy controller

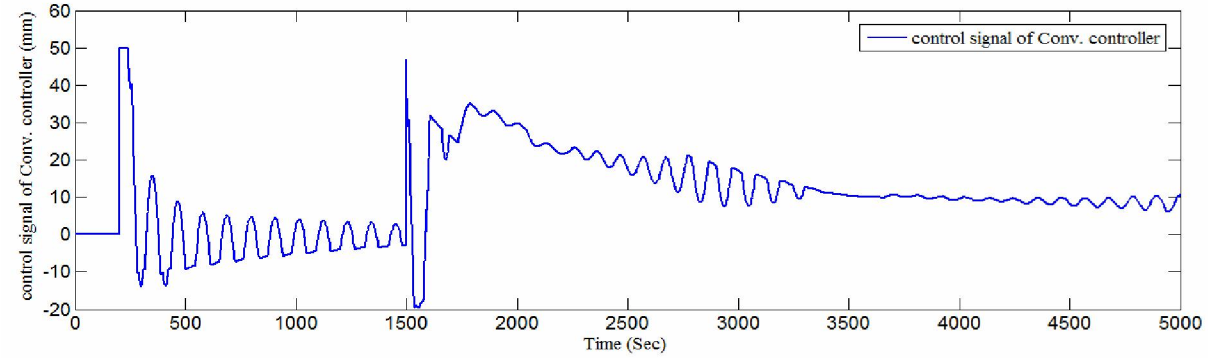

Fig. 8. (a) Control signal of conventional controller (mm)

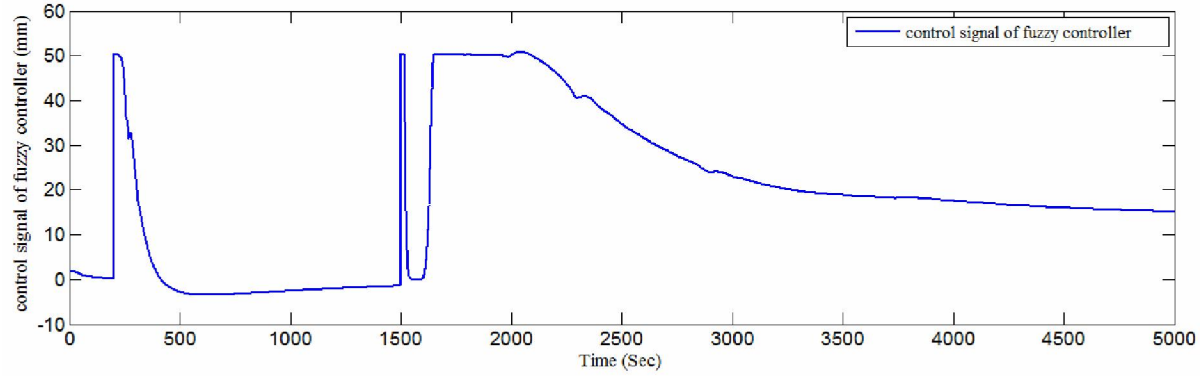

Fig. 8. (b) Control signal of fuzzy controller (mm)

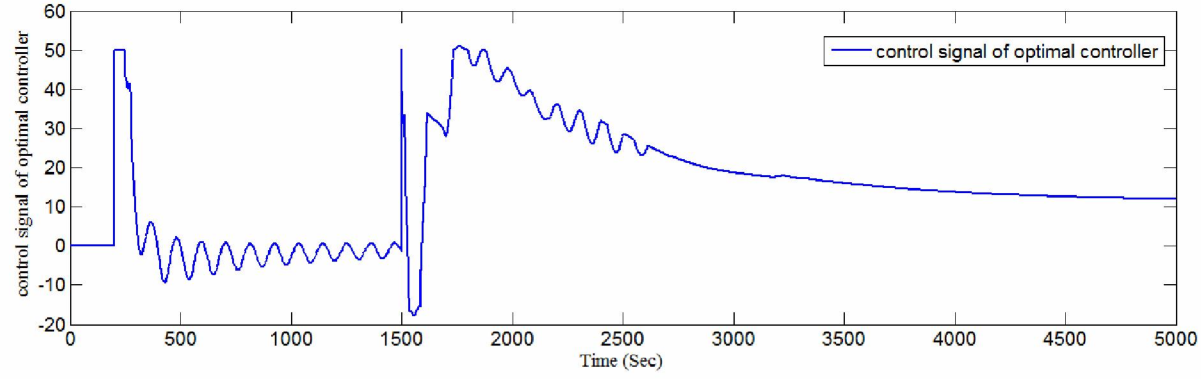

Fig. 8. (c) Control signal of optimal fuzzy controller (mm)

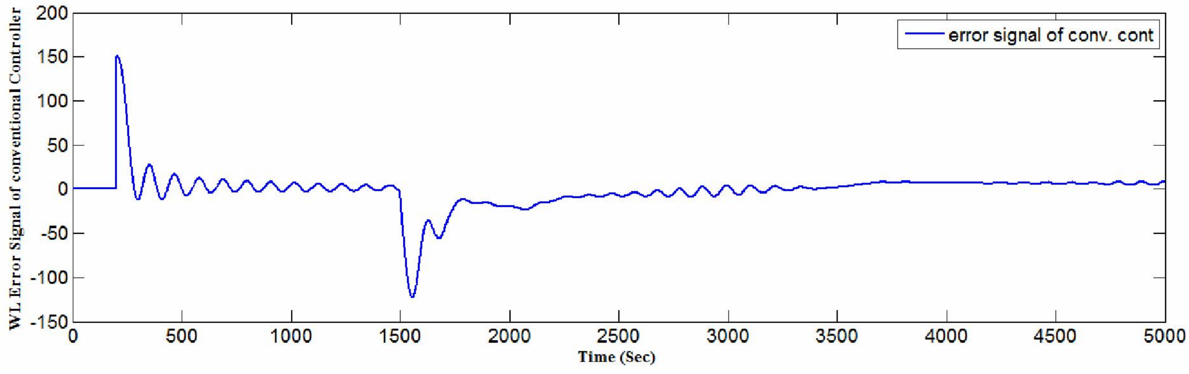

Fig. 9. (a) Water level error signal of conventional controller (mm)

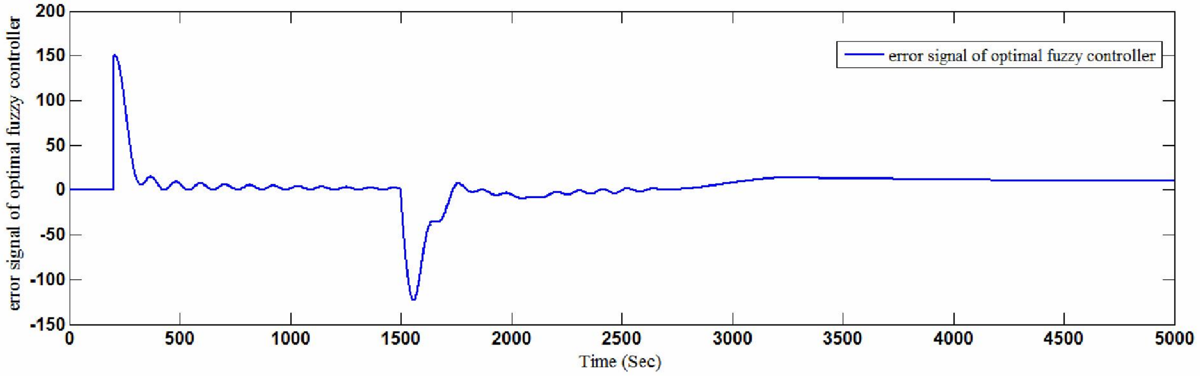

Fig. 9. (b)Water level error signal of fuzzy controller

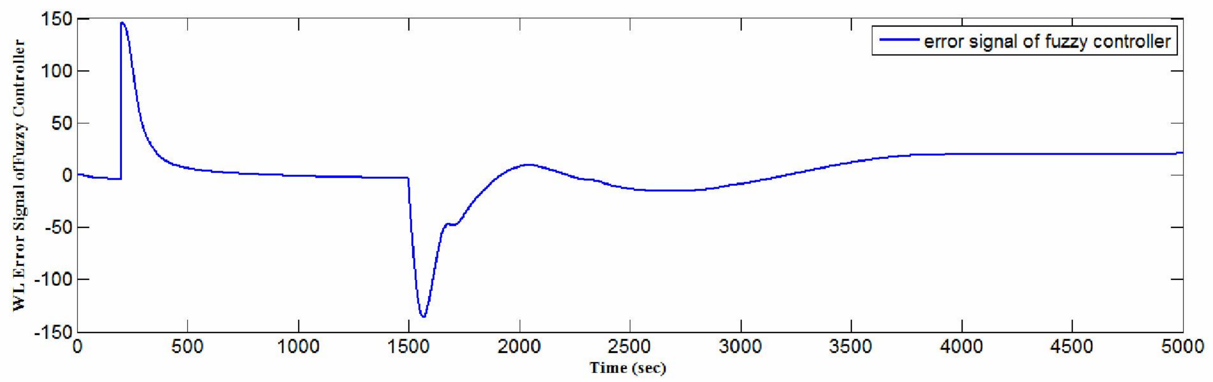

Fig. 9. (c) Water level error signal of optimal fuzzy controller (mm)

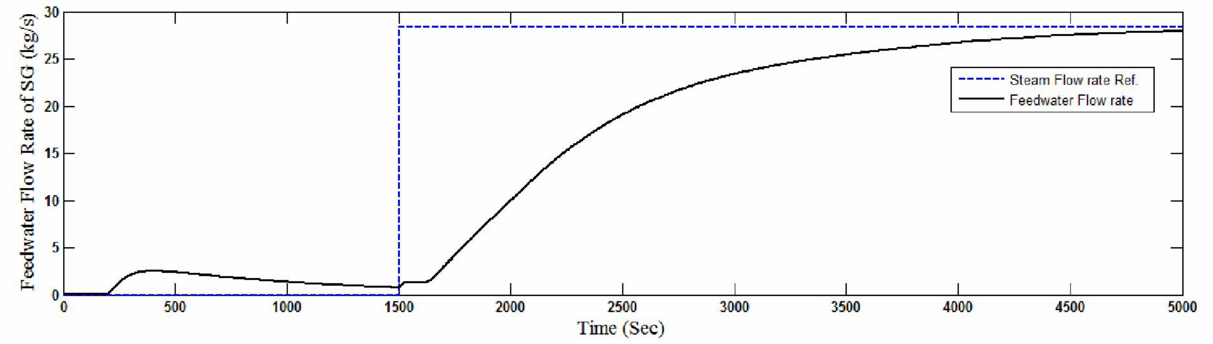

Fig.10. Feedwater flow rate of steam generator when steam flow rate is 28.4 kg/s

References

1. Cheng Liu, Fuyu Zhao, Ping Hu, et al. P controller with partial feed forward compensation and decoupling control for the steam generator water level [J]. Nuclear Engineering and Design, 2010, (240):181-190
2. Ke Hu, Jinqi Yuan. Multi-model predictive control method for nuclear steam generator water level [J]. Energy Conversion and Management, 2008, (49):1167-1174
3. Mohand Si Fodil, Patrick Siarry, Francois Guely, et al. A fuzzy rule base for the improved control of a pressurized water nuclear reactor [J]. IEEE Transactions on Fuzzy Systems, 2000, 8(1):1-10
4. H. Habibiyan, S. Setayeshi, H. Arab-Alibeik "A fuzzy-gain-scheduled neural controller for nuclear steam generators", Annals of Nuclear Energy, Volume 31, Issue 15, October 2004, Pages 1765-1781.
5. S. M. Elaraby, “Automatic Reactor Power Stabilization Control using Proportional Integral Derivative Approach”, EAEA/Int. Rep. No. 229, 28 (1998).
6. K. M. Mostafa, “Fuzzy Logic Controller for Automatic Nuclear Power Station” M.Sc. Thesis, Faculty of Engineering, Cairo University (1998).
7. H.M. Emarah, A. Elsadat, A. Bahgat, and M. Sultan, “Powers Stabilization of Nuclear Research Reactor via Fuzzy Controllers”, American Control Conference, Anchorage, AK May 8-10 (2002).
8. S. B. Kuzmanovic and L. Emil; Engineering Applications of Artificial Intelligence; 14, 785 (2001).
9. E. Irving, C. Miossec, and J. Tassart, “Toward efficient full automatic operation of the PWR steam generator with water level adaptive control,” in Proc. Int. Conf. Boiler Dynamics Contr. Nuclear Power Stations. London, U.K., 1980, pp. 309–329.
10. Matlab/SIMULINK User Guide’s, The MathWorks, Inc. (2008).
11. Jhon. R Lamarsh,”Introduction to Nuclear Reactor Theory”, Addison-Wesley Publishing Company, USA (1972).
12. Zuheir Ahmed, “Data-driven controller of nuclear steam generator by set membership function approximation”, annual of nuclear energy, Vol. 37, pp. 512-521, 2010.
13. R. R. Yager and D. P. Filev, ”Essentials of Fuzzy Modeling and Control”, Joh Wiley & Sons, New York (1994).

14. B. Hu, K.I. George, and R.G. Gosine ; IEEE Trans. Fuzzy Syst; 7 (5), 521 (1999).
15. J. Jantzen, “Tuning of Fuzzy PID Controllers” Technical Report 98-H871, Department of Automation, Technical University of Denmark (1998).
16. M. Gyun-Na; IEEE Transactions on Nuclear Science; 45 (4), 312 (1998).
17. F. Herrera and M. Lozano, “Adaptation of Genetic Algorithm Parameters Based on Fuzzy Logic Controllers”, Technical Report 18071, University of Granada, Granada, Spain (1996).
18. D.E. Goldberg, "Genetic Algorithms in Search, Optimization, and Machine Learning", Addison-Wesley Publishing Company, USA (1989).
19. O. Cordon, F. Gomide, F. Herrera, F. Hofmann and L. Magdalena; Fuzzy Sets and Systems; 141, 5 (2004).
20. F. Joseph, “Fuzzy Controller Optimization using Genetic Algorithms”, M.Sc Dissertation, School of Electronic Engineering, Dublin City University. Ireland (2002).
21. J. P. Byrne, “GA-Optimization of a Fuzzy Logic Controller” M.Sc Project 50222465, School of Electronic Engineering, Dublin City University. Ireland (2003).
22. S. C. Bariloche and P. Negro; Brazilian Journal of Chemical Engineering; Argentina, 19(4), 441 (2002).
23. P.L. Lanzi, W. Stolzmann, and S.W. Wilson, “Learning Classifier Systems: from Foundations to Applications”, Lecture Notes in Computer Science, Springer, Berlin (2000).
24. W. Caminhas, H. Tavares, F. Gomide and W. Pedrycz; Journal Advanced Computer Intelligent; 3 (3), 151 (1999).
25. M. Marseguerra, E. Zio and F. Cadini; Annuals of Nuclear Energy; 32, 712 (2005).
26. A. Maidi, M. Diaf and J. P. Corriou; Chemical Engineering and Processing; Corrected Proof, Available online, 28 March (2007).
27. A. Chipperfield and P. Feliming “Genetic Algorithm Toolbox for Use with MATLAB, User’s Guide” Department of Automatic Control and System Engineering, University of Sheffield, GR/J17920 (1993).
28. E. Rustighi, ”Dynamics of Rotating Machinery: Analysis, Identification and Control”, Ph.D. Thesis, Department of Mechanical, Nuclear and Production Engineering, University of Pisa, Italy (2004).

3/25/2011