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A 9-Rule Fuzzy Logic Controller of the Nuclear Steam Generator

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핵증기 발생기의 9룰 퍼지논리 제어기

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Abstarct

A model free controller utilizing a set of linguistic fuzzy logic of the human operator's experience is developed to control the steam generator water level in a pressurized water reactor.

Only 9 rules for control action are generated from the inputs of water level error and mass flow error implicitly representing the time variation of the collapsed water level.

The bell type membership functions of the premise side and the result side are tuned by the sensitivity study. This compact fuzzy logic controller shows a robust control during transient and no offset error and oscillation during steady state operation. For a multi-ramp power increase from start-up to full power, the proposed controller shows good performance for the entire range.

요 약

운전원의 언어적인 제어 논리를 이용한 모델과 무관한 제어기가 증기 발생기의 수위 제어를 위해 개발되었다. 오직 9개의 룰을 수위 오차와, 응축 수위 변화를 표현하는 유량 오차로 부터 얻어졌다. 벨형의 소속함수는 민감도 분석을 통하여 조절되었고, 결과 과도 상태와 정상상태 공히 양호한 제어성능을 보였다. 저출력에서 전 출력까지의 다단계 출력 증가에 대하여, 전 운전 영역에서 좋은 제어를 보였다.

1. Introduction

Fuzzy logic control(FLC) scheme is generally considered as a robust controller for a very complex or human–like system. Also, it is widely accepted that FLC is one of strong candidates able to supersede the manual control for many industrial process equipments because FLC is constructed from the skill of the human operator. The manual control retarding the progress in the instrument–and–control system of the nuclear power plant has been done for the nuclear steam generator at the low power, below 25% of the rated power, because of the reverse dynamics of the water level, named as swell–and–shrink phenomena[1]. To replace it, many controllers have been proposed and they can be classified according to their dependency on the system model : the model–base controller[1], the model–reference controller[2,3], and the model–free controller [4,5]. If we acknowledge the deviation between the model and the real system, the controllers less depending on the model seem to be more robust then the other controllers, when they are implemented in the real system. Among the model free controllers : an artificial intelligent controller, a neural network controller, and a fuzzy logic controller, FLC has benefits of the well structured knowledge and the numerical signal treatment[6]. The major drawbacks of the FLC are its rule generation method and its optimization are not clearly developed yet. Recent researches have been done to find an easy and systematic way to get an optimized logic by partially connecting FLC to the technique of neural network and parameter estimation scheme of the adpative controller[6]. A few applications of FLC are reported in the nuclear industry[4,5]. The FLC of the nucelar steam generator[5] by Kuan et al. has many rules (more than 50) which are not fully optimized. Their ways to show their contribution are to represent several results of the sensitivity study and the possibility of the ramp power increasing from the low power to the full power. Their rules are strongly depend on the change of the steam flow rates.

This large rule matrix prevents us from getting the well tuned controller and from transplanting it easily to the other nuclear steam generators. The practical question is how many rules are required to control the steam generator. In this paper, a compact FLC for the steam generator is developed with only 9 rules made of the know–how of the skilled operator's control action when the level shows swell–and–shrink phenomena.

2. Steam Generator Model

To test the controller, a dynamic model of the steam generator is used. This model was already used to generate the scaling laws of the nuclear steam generator for the experimental evaluation of the performance of the various controller[7] and to give dynamic response in the real–time simulator of Korea Nuclear Unit 2.[8].

Mass and energy conservation equations for three nodes of the boiling region, the steam dome region, and the downcomer region and a momentum equation generated by integrating along the entire circulation loop are used. The sophisticate prediction of the bubble departure point and the mass and energy integration in the boiling region make the model represent the swell–and–shrink phenomena from the perturbation of feedwater flow as well as that of steam flow [1,8].

3. Fuzzy Control Model for Operators

The fuzzy controller has three steps of input

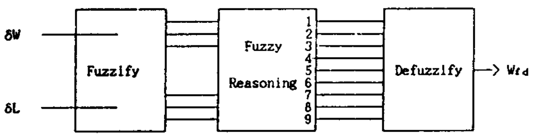


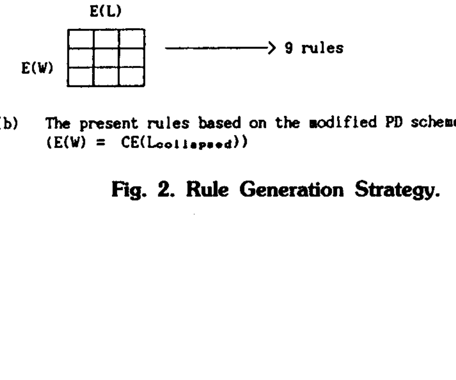
Fig. 1. Structure of the Fuzzy Reasoning.

fuzzification, fuzzy reasoning, and defuzzification for actuator as shown in Fig.1 :

3.1. Generation of the Fuzzy Control Rules

Mamdani's rule generating method[9] based on error(DE) and the change of error(CE) is widely accepted because it is simple and related with the conventional PD controller. There are several other methods are suggested to couple the PID controller with fuzzy controller. However, the rule generation method based on PD inputs could give us two sets of rules for level and mass flow rate if we follow the conventional three elements control scheme of the nuclear steam generator. Even though we use only three lingustic term for the fuzzification of inputs, there are more than 19 rules : 9 rules from level error, 9 rules from mass flow error, and more than one rule to combine these two sets of rules. To reduce the size of rule matrix, we try to choose only two coordinates of the level error and mass flow error for the rule matrix which generate only 9 rules as shown in Fig 2.

Since these rules are constructed by the proportional errors of the level and mass flow rate, a large offset error and some instability are expected



(a) The conventional rules based on the PD scheme for three elements inputs

(b) The present rules based on the modified PD scheme ($E(W) = CE(L_{collapsed})$)

Fig. 2. Rule Generation Strategy.

but the developed controller works well. However the mass flow rate error implicitly represents the time variation of the collapsed water level. After the thermal effect is settled down, the total mass conservation equation of the steam generator represents the time variation of the collapsed water level :

$$\frac{d(M_{sg})}{dt} = W_{fd} - W_{st} = \tau \frac{dL_{collapse}}{dt} \quad (1)$$

Therefore, the present rule matrix is a modified form of rules based on PD action suggested by Mamdani et al. The problem of the measurement error of the mass flow rate at the low power level could be resolved by using the energy conservation relation with the more accurate signal of the core power and the first stage steam pressure in the high pressure turbine. From the pressure in the turbine, the steam flow rate, W_{st}, and steam enthalpy, h_g, are estimated. Also, from the temperature sensor at the feedline, the feedwater enthalpy is measured. The mass flow rate error could be estimated by using the following relation with the core power measured from the neutron flux :

$$W_{st} - W_{fd} = W_{st}(1 - h_g/h_{fd}) + Q_{core}/h_{fd} \quad (2)$$

Besides the small number of rules, the present fuzzy logic is directly related with the know–how of operators who control the steam generator according to the swell–and–shrink phenomena. If we define the mass flow rate error(E(W)) as the steam flow rate(W_{st})–the feedwater flow rate(W_{fd}) then the water level swells when E(W) is positively big(PB), the water level shrinks when it is negatively big(NB), and the water level slightly oscillates up–and–down when it is near zero(ZO). The control actions are classified in five linguistic terms : positively big(PB), positively medium(PM), near zero(ZO), negaitively medium(NM), negatively big(NB). Let us construct the control rule for these mode :

a) Control rule for the swelling mode

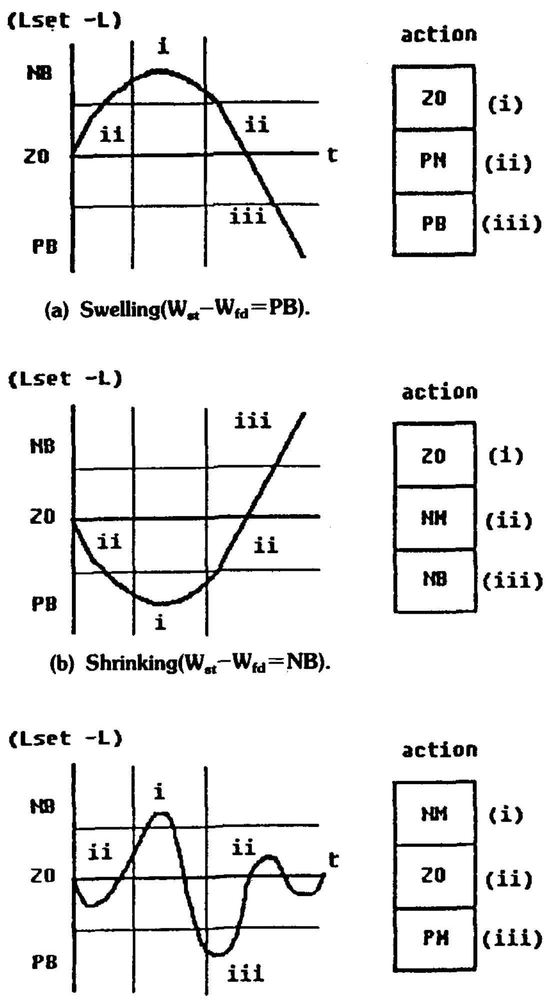
If E(W) is positively big(PB) then the water level swells temporarily as shown in Fig. 3–a. If the water level error(E(L)), level set point–level, is devided by three linguistic degrees of positively big(PB), near zero(ZO), and negatively big(NB), the control actions of the operator are rule 3, 6, and 9 in Fig 4.

b) Control rule for the shrinking mode

If E(W) is negatively big(NB) then the water level temporarily shrinks and increases as shown in Fig. 3–b, the control action of the operator are rule 1, 4, and 7 in Fig. 4.

c) Control rule for the normal mode

If E(W) is near zero(ZO) as shown in Fig. 3–c, the control action of the operator are rule 2, 5, and 8 in Fig.4.



(a) Swelling($W_{st}-W_{fd}$=PB).

(b) Shrinking($W_{st}-W_{fd}$=NB).

(c) Normal Case($W_{st}-W_{fd}$=ZO).

Fig. 3. Control Rules Based on the Swell–and–shrink Phenomena.

$E(W) = W_{st} - W_{fd}$

NB	ZO	PB	$E(L) = L_{set} - L$
NB (rule1)	NM (rule2)	ZO (rule3)	NB
NM (rule4)	ZO (rule5)	PM (rule6)	ZO
ZO (rule7)	PM (rule8)	P[illegible] (rule9)	PB

Fig. 4. The Fuzzy–rule Map for the Steam Generators.

3.2. The Membership Functions for Inputs and Outpus

Since we want to control the water level with the minimum number of the rules, only three bell–type membership functions of NB, ZO, and PB are used for the fuzzification of the inputs.

$$\mu^{x}(ZO)=\exp(-x^2/\sigma^2) \quad \text{for} -\infty<x/\sigma<\infty \tag{3}$$

$$\mu^{x}(NB)=\begin{cases}\exp(-(x/\sigma+2)^2) & \text{for } x/\sigma>-2\\ 1 & \text{for } x/\sigma<-2\end{cases} \tag{4}$$

$$\mu^{x}(PB=\begin{cases}\exp(-(x/\sigma-2)^2) & \text{for } x/\sigma>2\\ 1 & \text{for } x/\sigma<2\end{cases} \tag{5}$$

where x is E(W) or E(L). The deviation σ_L for water level error can be defined by the physical unit of mm, since the level set point and error boundary is not changed according to the power level. Although the error range of the mass flow rate could be wide, error range is proportional to the standard mass flow rate of the given power. The deviation for the membership function of the mass flow rate error is expressed as

$$\sigma_W = k1\ W_{ref}(Q), \tag{6}$$

where $W_{ref}(Q)$ is the steam flow rate at the power of Q.

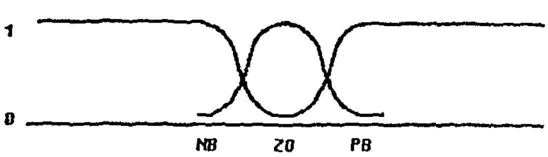


Fig. 5. The Membership Function for Inputs.

Also, the membership functions for control action represented in the Fig.4 have 5 linguistic values of PB, PM, ZO, NM, and NB which are

$$\begin{aligned}
&\mu_{wfd}(NB) = \exp[-(x/\sigma_{wfd}+4)^2],\\
&\mu_{wfd}(NM) = \exp[-(x/\sigma_{wfd}+2)^2],\\
&\mu_{wfd}(ZO) = \exp[-(x/\sigma_{wfd})^2],\\
&\mu_{wfd}(PM) = \exp[-(x/\sigma_{wfd}-2)^2],\\
&\mu_{wfd}(PB) = \exp[-(x/\sigma_{wfd}-4)^2],
\end{aligned} \tag{7}$$

where

$$\sigma_{wfd} = k2\ \sigma_w \tag{8}$$

The above membership functions have three tuning parameters of σ_L, k1, and k2 which are less than the three-elements controller having more than four parameters.

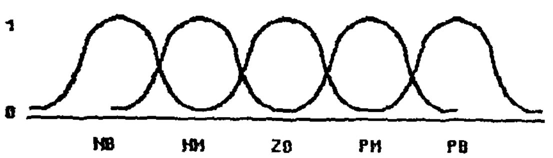


Fig. 6. The Membership Function of the Control Action.

3.3. Fuzzy Inference and Defuzzification

A direct reasoning method proposed by Zadeh [10] is used here. In this method, the value of the membership function of input is examined at first for individual rule and the output depending on this value is determined. Then the final output is calculated by averaging the whole rule, as follows ; The output feedwater increasing $D(W_{fw})n$ of n-th rule is given by

$$D(W_{fw})_n = \min[\mu_W^n(E(W)),\ \mu_L^n(E(L))]\ \mu_{wfd}^n, \tag{9}$$

where $\mu_W^n(E(W))$ and $\mu_L^n(E(L))$ are the membership function of the premise side for the input error of the mass flow rate and the water level, respectively. The degree of premise side is chosen as the smaller one of two-premise membership functions. And the output of the feedwater increasement $D(W_{fw})_n$ from n-th rule is given by the values of the conclusion membership function μ_{wfd} multiplied by this degree of premise side.

The final control action is determined by taking the center of mass the output membership function as

$$W_{fd}^{n+1} = W_{fd}^{n} + \frac{\int_{-\infty}^{\infty} \max(D(W_{fd})_n)\ x\ dx}{\int_{-\infty}^{\infty} \max(D(W_{fd})_n)\ dx} \tag{10}$$

The above defuzzification stage is easily calculated by using the approximation function by E.Page [11] :

$$\int_{-\infty}^{x} e^{-1/2\,u^2} du = (\pi/2)^{1/2}(1+\tanh(y)) \tag{11}$$

wher

$$y = (2/\pi)^{1/2} \times (1+0.04482360x) \tag{12}$$

4. Results and Discussions

The fuzzy controller suggested here is implemented by the steam generator model describing the reverse dynamics of water level [7]. To get the optimum shape of the membership function, we take computational experiments to get the

FLC showing the short rising time, small overshoot, and fast damping.

Tuning the parameters for the membership functions is done with ease by developing a software tool showing the time variation of the water level, control action, and shape of the membership function as shown in Fig.7. User easily changes the parameters of the membership function, the operating power range, even fuzzy rules by clicking the mouse on the pull down menu of this software tool. Also, conventional PID controller is equipped to compare it with the Fuzzy logic controller. This tool is working on a personal computer of IBM-PC compatible having the super VGA board and the micro mouse compatible.

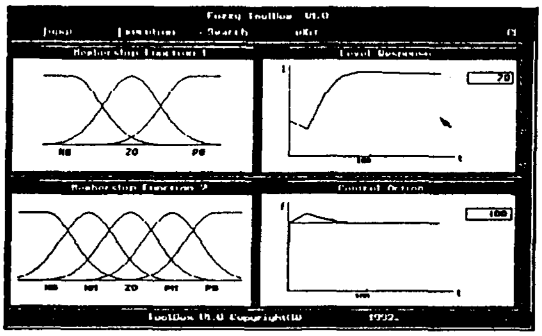


Fig. 7. The Fuzzy Tool Box for the Sensitivity Study.

4.1. Sensitivity Study

A reference transient is selected to do the sensitivity study of FLC by increasing the set point of the water level up to 100mm at 0 sec, step increasing the steam flow rate to 0.4% of the rated steam flow at 2000 sec, and sudden decreasing it to 0.8% of the rated steam flow rate at 2500 sec.

(a) Sensitivity study at 5% power

At this low power, the swell-and-shrink phenomena is dominant. A number of simulation are done by changing three parameters of membership functions : 200mm< σ_L<2000 mm, 0.01 <k1<2.0, and 0.01<k2<7.0.

General statements obtained from these sensitivity study are :

-Rapid response and large overshooting occur as k1 increases.

-As k2 increases, large ocillation or control failure occurs because of large control action.

-At 5% power, the reasonable control response occurs when the ratio of (σ_L/k1) is about 1000.

Since the full representation of the results of the sensitivity study is meaningless, two sets of the representative responses are presented here. Figures from 8 to 11 have two parts : the upper part shows the level response and the lower part shows the perturbation of the steam flow rate with the solid line and the response of the feedwater mass flow rate in the dotted line. The numbers in the parenthesis represnt σ_L, k1, and k2, respectively.

The water level response by the fuzzy controller with σ_L=200mm, k1=0.2, and k2=0.01 shown in Fig. 8 is very similar to that by the fuzzy controller with σ_L=1000mm, k1=1.0, and k2=0.01 shown in Fig.9. But these figures show the slow response due to small k2. Figures 10 and 11 show effect of k2 value by changing it from 0.01 to 1.0. The FLC with these value for the membership functions shows quick response than that with k1 =0.01. From this comparison k2 is recommended as 1.0.

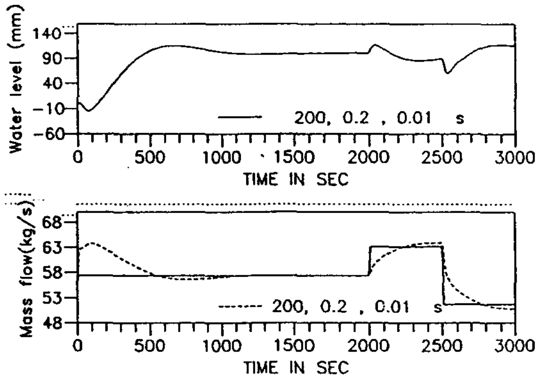


Fig. 8. Fuzzy Control of the Steam Generator(200, 0.2, 0.01) for 5% Power.

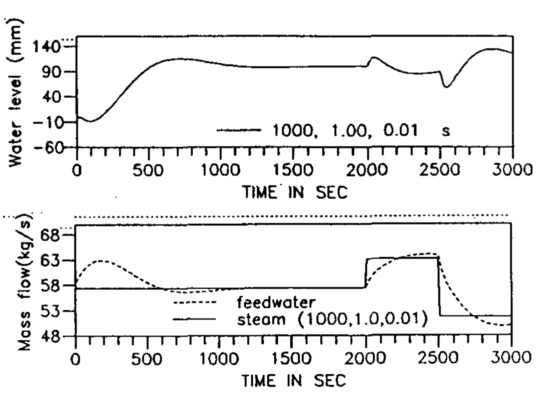


Fig. 9. Fuzzy Control of the Steam Generator with(1000, 1.0, 0.01) for 5% Power.

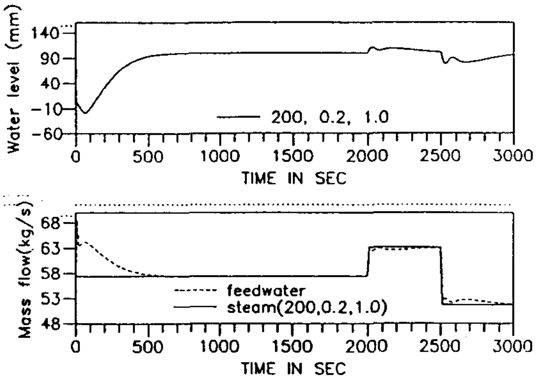


Fig. 10. Fuzzy Control of the Steam Generator with(200, 0.2, 1.0) for 5% Power.

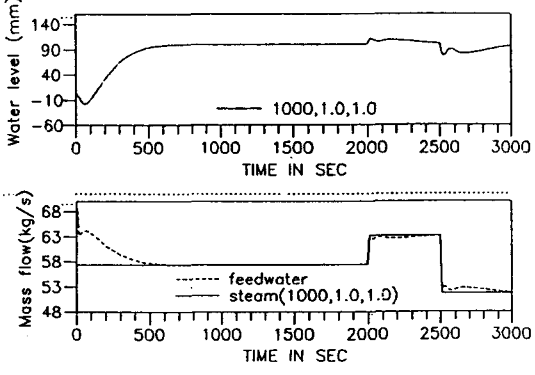


Fig. 11. Fuzzy Control of the Steam Generator with(1000, 1.0, 1.0) for 5% Power.

(b) sensitivity study at 100% power

Sensitivity study shows that good response occurs when $(\sigma_L/k1)$is near 2000 at the rated power. The FLC having the ratio $(\sigma_L/k1)=2000$ shows slow but stable response for the 5% power. The slow response at the low power does not make any serious problem because slow startup is needed to do other operating procedure at the low power.

4.2. Comparison to PI Controller

It is not favorable to vary the gains of PI controller or the membership functions of FLC as a function of the power because it reduces the transplantability of the controller and needs large tuning efforts when the state of the system drifted from the original state. We want to check which controller controls robustly the steam generator in a broad operating range, when their gains or shape of the membership function are fixed to the values tuned at 100% power or 5% power for the same perturbation used in the sensitivity study.

As shown in Fig. 12, the PI controller of the gains tuned for the 100% power fails to control below the 30% power level due to large oscillation. The level response for 50% power is similar to the 100% power because of small swell–and–shrink phenomena due to the feedwater. The PI controller of gains for 5% power succeeds in con-

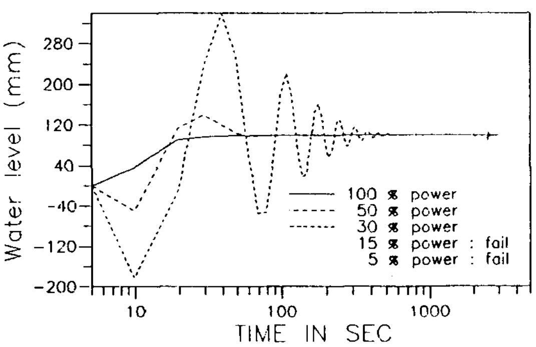


Fig. 12. PI Control of the Steam Generator Based on the 100% Power Control Efficiency.

trol for all over the power range as shown in Fig. 13, but its response is too slow at high power where fast response is required to follow the fast perturbation from the turbine and reactor core.

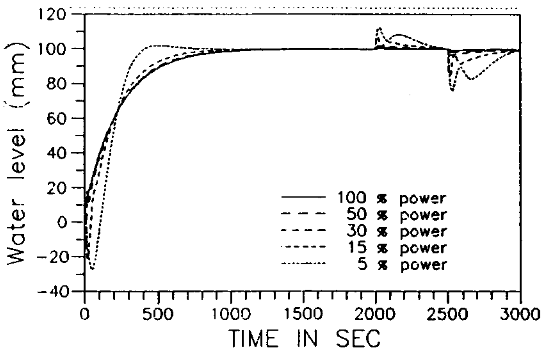


Fig. 13. PI Control of the Steam Generator Based on the 5% Power Control Efficiency.

The Fuzzy Controller tuned at 100% power does not fail in any power range as shown in Fig.14. The slow response at low power is not a critical problem in the steam generator operation. The response of FLC tuned at 5% power shows large overshoot at the high power for the level set point perturbation but the level perturbation due to the steam flow rate change is not large as shown in Fig. 15. It can be recommended that the FLC tunned at the 100% power is the standard fuzzy logic controller for the nuclear steam generators.

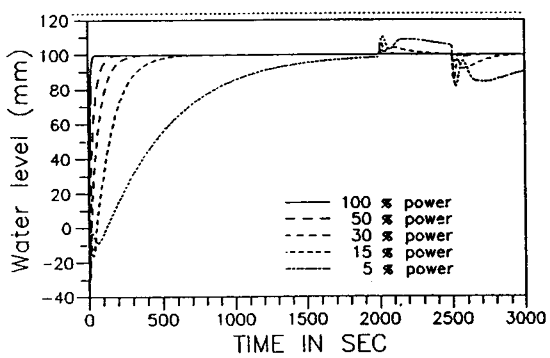


Fig. 14. Fuzzy Control of the Steam Generator Based on the 100% Power Control Efficiency.

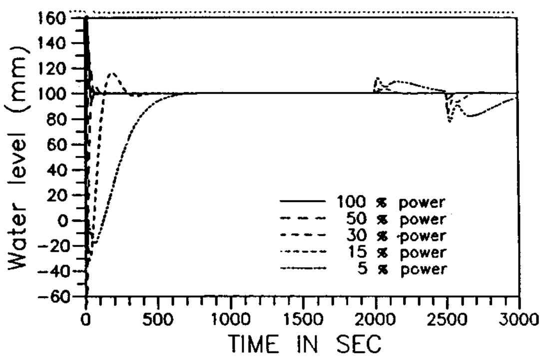


Fig. 15. Fuzzy Control of the Steam Generator Based on the 5% Power Control Efficiency.

4.3. Multi-ramp Power Increase

A test is done with a multi-ramp power increase from start-up to full power, the proposed FLC shows good performance for the entire power range as shown in

Fig. 16. The power level is increased by 5% during 1 min and then kept constant for 9 min before another step. As shown in Fig. 17, the control action is done in a robust way of no frequent oscillation. Of course the conventional PI controller could not perform this operation due to large oscillation in the low power.

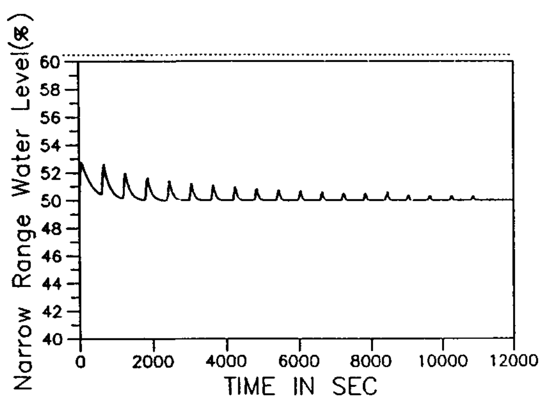


Fig. 16. The Water Level Response for the Multi-ramp Power Increase with Fuzzy Controller.

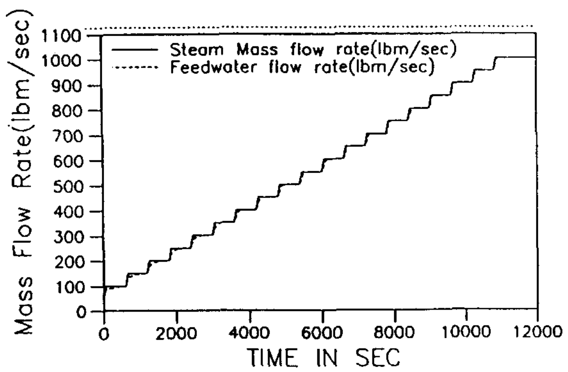


Fig. 17. The Fuzzy Control Action for the Multi–ramp Power Increase.

5. Conclusion

Based on the above discussions, the following conclusions can be made :

(1) A compact FLC with 9 rules for the steam generator is developed by directly combining the inputs of the level error and the mass flow rate error which represents implicitly the time variation of the collapsed water level.

(2) This direct combination of level error and mass flow rate error gives us physically clear control rules between the operator's control action and the swell–and–shrink phenomena.

(3) The membership functions are tuned by performing the sensitivity study.

(4) Comparison between the present FLC and the conventional PI controller shows the FLC is more robust in all operating range than PI controller.

(5) The present FLC has no problem in controlling the water level for the ramp power–up from the low power to the rated power.

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