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Fuzzy Algorithms to Generate Level Controllers for Nuclear Power Plant Steam Generators

Byung Soo Moon, Jae Chang Park, Dong Hwa Kim, and Byung Koo Kim
Korea Atomic Energy Research Institute
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원전 증기 발생기 수위제어용 퍼지 알고리즘

문병수 · 박재창 · 김동화 · 김병구
한국 원자력 연구소
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Abstract

In this paper, we present two sets of fuzzy algorithms for the steam generater level control ; one for the high power operations where the flow error is available and the other for the low power operations where the flow error is not available. These are converted to a PID type controller for the high power case and to a quadratic function form of a controller for the low power case. These controllers are implemented on the Compact Nuclear Simulator at Korea Atomic Energy Research Institute and tested by a set of four simulation experiments for each.

For both cases, the results show that the total variation of the level error and of the flow error are about 50% of those by the PI controllers with about one half of the control action. For the high power case, this is mainly due to the fact that a combination of two PD type controllers in the velocity algorithm form rather than a combination of two PI type controllers in the position algorithm form is used. For the low power case, the controller is essentially a PID type with a very small integral component where the average values for the derivative component input and for the controller output are used.

요 약

원전증기 발생기 수위제어용 두개의 퍼지 알고리듬을 개발하였다. 즉, 증기 및 급수유량사용이 가능한 고출력 경우와 이들의 사용이 불가능한 저출력시등 용도를 분리하여 별도의 알고리듬으로 개발한 것이다. 이들 알고리듬은 고출력시의 경우 PID형태의 제어기로 변환시켰고 저 출력시의 경우 2차함수 형태의 제어기로 변환시켰다.이들제어기는 한국원자력 연구소 보유 Compact Nuclear Simulator에서 각각 4개의 모의 운전을 통하여 실험하였다.

실험결과, 두 경우 모두 Simulator에서 사용되고 있는 PID제어기에 비하여 약 50%의 제어량으로 수위곡선 및 유량차이의 총 변화량이 절반이하가 되도록 제어가 가능했다. 고출력의 경우, 이는 수위 및 유량등을 입력으로 하는 PI제어기 대신 같은 입력의 PD제어기를 속도 알고리즘으로 사용한 점이 근본적인 차이로 볼 수 있으며 저 출력시의 경우는 수위를 입력으로 하는 PI제어기 대신에 적은 비율의 'I'성분을 포함하는 PID제어기를 사용하였으며 'D'성분입력과 제어기 출력에 각각 평균값을 사용한 것이 주 차이점이라 할 수 있다.

1. Introduction

In nuclear power plants, the water level of the steam generators must be maintained within the predefined limits. The upper limit is set to protect the turbine from too much moisture and the lower limit is set for the safety reasons. A violation of the limits would cause an automatic reactor trip or a turbine trip.

During the low power operations (usually less than 20% of the rated power), one of the major difficulties in the level control is due to the lack of the accuracy of the measured values for the steam flow out and the feedwater flow in. The errors are so big that they can not used as inputs to the level controller.

Another source of difficulty during the low power operations is that the level of the steam generators experiences the swell and shrink problems as the steam dump valve opens or closes,i.e. as the pressure in the steam generators changes rapidly. The sudden changes in the amount of the feedwater flow or the temperature of the feedwater in the steam generators would also cause some swell and shrink effects to the water level.

There have been many studies on how to handle the swell and shrink problems properly. In [1], a controller is proposed to compensate the water level for the swell and shrink effects so that the unnecessary control action can be reduced. In [2], we find a control strategy to physically suppress the swell and shrink effects, i.e. to quickly open the feedwater valves fully when fast load-down is initiated and to quickly reduce the water inventory during fast load-up.In [3], we find an actually implemented and industrially applied control scheme where an estimation of the steam flow by the steam pressure is used.

Recently, fuzzy logic controllers are introduced in many applications for replacements of the PID-(Proportional-Integral-Derivative) controllers. It is shown [4, 5] that a fuzzy logic controller can be designed so that it is equivalent to a PID controller for single input linear system and is better in nonlinear process system.

A fuzzy logic controller for the nuclear steam generator level control with two input signals is found in [6]. It was designed, implemented and tested on a nuclear simulator for the Fugen nuclear power plant in Japan. In all of these cases, fuzzy logic controllers are found to be better in the sense that almost all of the overshooting effect is eliminated.

In this paper, we present two sets of fuzzy algorithms for the steam generator level controller, one for the high power case and the other for the low power case. These are designed, implemented and tested on the Compact Nuclear Simulator at Korea Atomic Energy Research Institute. The simulator was built to simulate various operational modes for the 900MWe Westinghouse PWR type nuclear power plants [8].

The fuzzy algorithms are then used to generate analytical equivalents, i.e. a PID type controller for the high power case and a quadratic function form of the controller for the low power case.

We make quantitative comparisons in terms of the total variation of the curves for the level error, the flow error and the control action. The integral of the absolute errors or the integral of the squared errors could have been used, but the total variation seems to be more practical for our purposes.

In our study on the swell and shrink effects through the nuclear simulator, the compensation of the water level by using the main steam header pressure or by using the dump valve openings has been tried in vein. Both curves are either off-timing or of different in nature in relation to the level curve. An adjustment of the controller gain by the feedwater temperature, however, was successful.

In an attempt to physically suppress the swell and shrink effects, we had to increase the controller gain unnecessarily high, which ended up causing an upset situation in the overall trend of the level curve for certain experiments.

Thus, in our fuzzy logic controller for the low power case, we have left with the level error as the only major input to the controller, while the derivative of the first stage pressure for the High Pressure Turbine(T_{ref} ; Reference Coolant Average Temperature) is used as an auxiliary input to represent the overall trend of the steam flow.

2. Fuzzy Logic Controller for the High Power Case

As mentioned above, the Compact Nuclear Simulator at Korea Atomic Energy Research Institute is designed to simulate various operational modes for the Kori 3 & 4 (900Mwe PWR type) nuclear power plants. A schematic diagram of the level controller for the steam generators in the simulator is given by Fig.1 and Fig.2, where the constants are slightly different from those of the actual plants.

A schematic diagram of our fuzzy logic controller for the high power case is as shown in Fig.3.

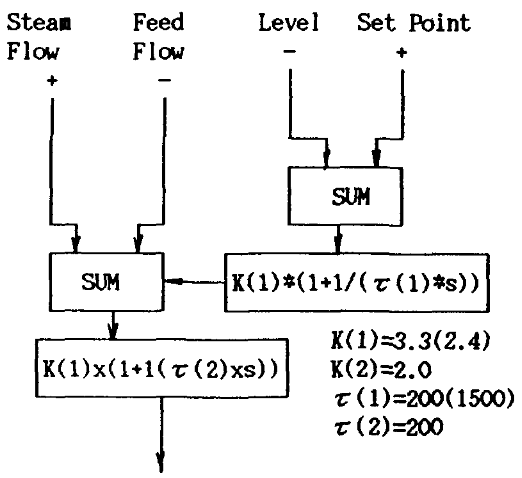

Fig. 1. PI Controllers for Main FW Valve
( ) : for actual plant

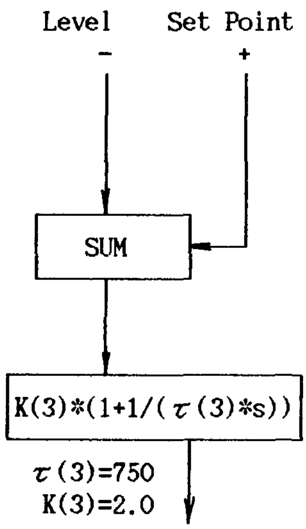

Fig. 2. PI Controller for FW Bypass Valve

We fuzzified the input variables of the level error, the flow error, the derivative of the level error, and the controller output as shown in Fig.4 through Fig.7. We have used the standard spike

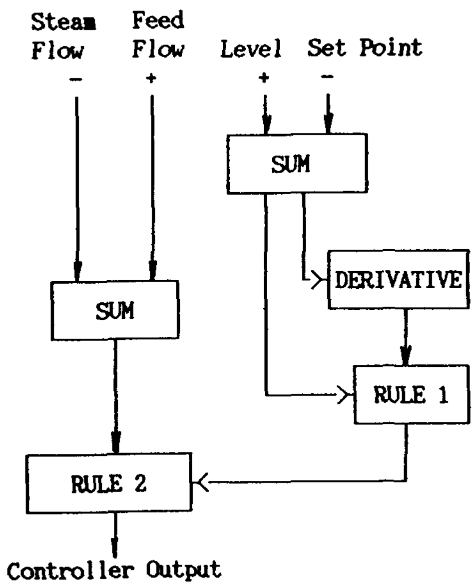

Fig. 3. Fuzzy Logic Controller (High Power Case)

functions as the membership functions of the seven fuzzy sets for the level error, the flow error and for the controller output. For the derivative of the level error, however, we have used the cubic B-spline functions[9] for a smoothing effect.

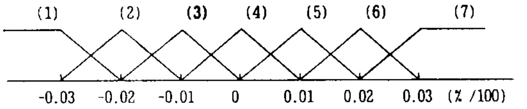

Fig. 4. Fuzzy Sets for Level Error

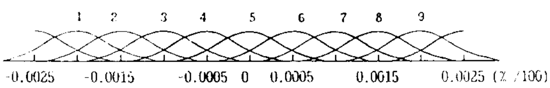

Fig. 5. Fuzzy Sets for Derivative of Level Error

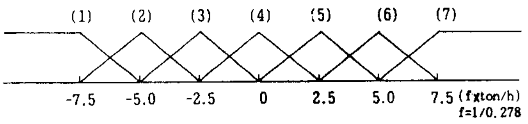

Fig. 6. Fuzzy Sets for Flow Error

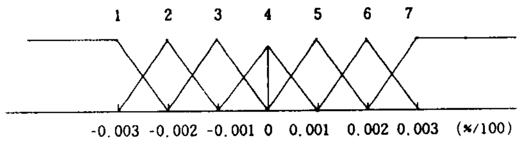

Fig. 7. Fuzzy Sets for Controller Output

For the high power case, 7 fuzzy sets are found to be enough for the level error, the flow error, and for the controller output, while 9 sets are used for the derivative of the level error. Note that all of the fuzzy sets are equally spaced and that the sum of the membership grades at each point on the x-coordinate line is 1. This fact will be necessary in computing an analytically equivalent form of the fuzzy logic controller as described in section 4.

For a given value of the level error, or of the flow error, there will be assigned a pair of fuzzy sets along with the membership grades for each. For the derivative of the level error, however, there will be a set of four fuzzy sets associated with a single value.

The pair of fuzzy sets and the corresponding membership grades for the level error are combined with the four sets and grades for the derivative of the level error by a set of fuzzy rules (RULE 1 in Table 1) to produce 8 sets with the corresponding membership grades. For the fuzzy set intersection operation, we have tried the product operation (Dubois & Prade with $\alpha=1$; [10]), and the classical minimum operation to find that the former is algebraically smoother and produces slightly better results for our simulation experiments.

Table 1. Fuzzy Control Rule 1 (LE vs ΔLE)

		Derivative of LE(ΔLE)								
		1	2	3	4	5	6	7	8	9
	1	1	1	1	1	1	2	3	4	5
	2	1	1	1	2	2	4	5	6	7
	3	1	1	2	3	3	4	5	6	7
LE	4	1	2	3	4	4	5	5	6	7
	5	2	3	4	5	5	5	6	7	7
	6	3	4	5	6	6	6	7	7	7
	7	4	5	6	7	7	7	7	7	7

Table 2. Fuzzy Control Rule 2 (LE+ΔLE vs FE)

		Flow Error(FE)						
		1	2	3	4	5	6	7
	1	7	7	7	7	6	5	4
	2	7	7	7	6	5	4	3
LE	3	7	7	6	5	4	3	2
+	4	7	6	5	4	3	2	1
ΔLE	5	6	4	4	3	2	1	1
	6	5	4	3	2	1	1	1
	7	4	3	2	1	1	1	1

For the fuzzy logic implications, we have tried the Mamdani's minimum operation rule and the Larsen's product operation rule [11]. The latter is found to be more suitable and produces better results, i.e. smaller total variation for our simulation experiments. We use the Larsen's product operation rule throughout this study.

The eight fuzzy sets produced by the intersection of the two sets for the level error and the four sets for the derivative through RULE 1 are combined and defuzzfied by the center of area method [11]. The resulting value is fuzzified by the fuzzy sets for the controller output(Fig.7) before it is fed into RULE 2 along with the flow error.

The two sets of rules RULE 1 and RULE 2 are generated based on the operating experiences and the common sense. Note that all of the entry blocks in both of the rule table matrices are filled in. This is necessary for computing the analytically equivalent form described in section 4. We have tried to make these rules so that they represent linear functions in two variables.

The resulting output from the second set of rules RULE 2 is a set of 4 fuzzy sets with membership grades for each and they are defuzzified by the center of area method using the fuzzy set in Fig.7. The computed value is used as the incremental value for the controller output so that our algorithm becomes a velocity algorithm in the high power case.

The tuning of our fuzzy logic controller was done to minimize the total variation of the control action, where the total variation of a function is the absolute integral of the derivative of the function.

The tuning work in this case is essentially the work of adjusting the boundary values for the support of the fuzzy sets for all of the related fuzzy variables. The numbers in Fig.4 through Fig.7 are all final values after the tuning work. We have selected one of the simulation experiments described in section 4 for the tuning of the fuzzy controller. The minimization of the total variation for the controller output was given the highest priority and the way to reach the minimum point was through the trial and error method.

3. Fuzzy Logic Controller for the Low Power Case

A schematic diagram of the fuzzy logic controller for the low power case is as shown in Fig.8. The inputs are the level error(LE) and the derivative of the Reference Coolant Temperature(ΔT_{ref}), while the output being the feedwater bypass valve position relative to the initial position.

Note that we are using the controller output as the valve position rather than as an increment of the valve position. More precisely, the output is used as the relative position of the bypass valve from the initial position.

Thus, our algorithm is a position algorithm rather than a velocity algorithm as used in the high power case. This is due to the fact that the

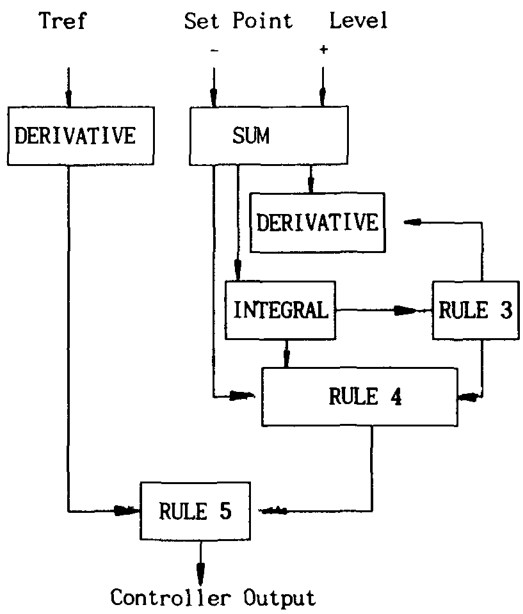

Fig. 8. Fuzzy Logic Controller (Low Power Case)

shrink occurs so sharply ; up to 10% drop in the level in less than 10 seconds at the simulator (Fig.17) when the nuclear power is at 16.8% before synchronization, that the velocity algorithm is not appropriate.

The input scanning period is 0.5 second and the average of the changes in the level error over a period of 10 seconds is taken for the derivative of the level error(ΔLE). We take the straight sum of the level errors from time zero up until now for the integral of the level error.

The fuzzy sets for the level error are exactly the same as those shown in Fig.4 except that we use eleven fuzzy sets by extending two sets on each side and that the numbers on the x–axis are scaled by a division factor of 0.7. Similarly, the thirteen fuzzy sets for the derivarive of the level error are the same as shown in Fig.5 with a division factor of 1.4.

The fuzzy sets for the integral of the level error and for the derivative of the Reference Coolant Temperature (ΔT_{ref}) are as shown in Fig.9 and Fig.10 respectively.

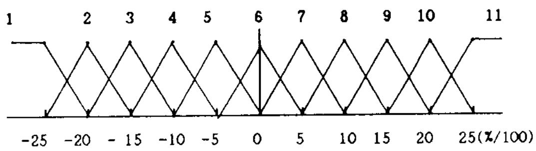

Fig. 9. Fuzzy Sets for Integral of Level Error

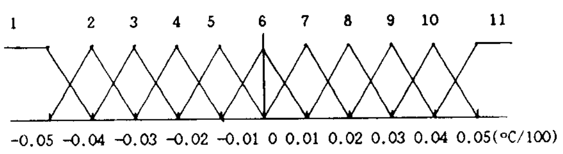

Fig. 10. Fuzzy Sets for Derivative of $T_{ref}(\Delta T_{ref})$

A combination of the derivative of the level error with the integral of the level error is done by a set of fuzzy rules RULE 3 shown in Table 3. As in the case of RULE 1, we perform fuzzy set intersections to generate 8 fuzzy sets with membership grades for each by RULE 3. These eight sets will be combined and defuzzified by the center of area method. The defuzzified value is fuzzified again before it is input to RULE 4.

Table 3. Fuzzy Control Rule (RULE 3) (ΔLE vs LE)

		LE										
		1	2	3	4	5	6	7	8	9	10	11
	1	1	1	1	1	1	1	1	1	1	1	1
	2	1	1	1	1	1	1	2	3	3	3	3
	3	1	1	1	1	1	2	3	4	5	5	5
	4	1	1	1	1	2	3	4	5	6	7	7
	5	1	1	1	2	3	4	5	6	7	8	9
	6	1	1	2	3	4	5	6	7	8	9	10
ΔLE	7	1	2	3	4	5	6	7	8	9	10	11
	8	2	3	4	5	6	7	8	9	10	11	12
	9	3	4	5	6	7	8	9	10	11	11	11
	10	5	5	6	7	8	9	10	11	11	11	11
	11	7	7	7	8	9	10	11	11	11	11	11
	12	9	9	9	9	10	11	11	11	11	11	11
	13	11	11	11	11	11	11	11	11	11	11	11

Table 4. Fuzzy Combination Rule (RULE 4) (ΔLE vs ΔLE+LE)

		ΔLE+LE										
		1	2	3	4	5	6	7	8	9	10	11
	1	1	1	1	1	1	1	2	3	4	5	6
	2	1	1	1	1	1	2	3	4	5	6	7
	3	1	1	1	1	2	3	4	5	6	7	8
	4	1	1	1	2	3	4	5	6	7	8	9
	5	1	1	2	3	4	5	6	7	8	9	10
LE	6	1	2	3	4	5	6	7	8	9	10	11
	7	2	3	4	5	6	7	8	9	10	11	11
	8	3	4	5	6	7	8	9	10	11	11	11
	9	4	5	6	7	8	9	10	11	11	11	11
	10	5	6	7	8	9	10	11	11	11	11	11
	11	6	7	8	9	10	11	11	11	11	11	11

In order to generate the rules in RULE 5, we observe the fact that as T_{ref} decreases, the pressure will build up in the steam generators and hence the feedwater flow decreases automatically without any change in the valve position. Thus, we have set the rules so that when T_{ref} decreases sharply, no control action is taken.

On the opposite case, however, note that the generator power can only be increased while we have excess nuclear power and hence the water level must experience the swell and shrink effects. Therefore, the swell effect due to the increase in the generator power is minor compared to the swell and shrink effects by the steam dump valve openings and closings. We have set our rules to reflect this fact.

Note also that if ΔT_{ref} is zero then the controller output should be proportional in the opposite direction, i.e. when $LE+\Delta LE+\int LE$ is 1 then the output is 11 and so forth. Thus, the first column, the last column and the one in the middle of table 5 are fixed. The rest are filled in by a linear interpolation.

Table 5. Fuzzy Control Rule (RULE 5) ($LE+\Delta LE+LE$ vs ΔT_{ref})

		ΔT_{ref}										
		1	2	3	4	5	6	7	8	9	10	11
	1	6	7	8	9	10	11	11	11	11	11	11
	2	6	6	7	8	9	10	11	11	11	11	11
	3	6	6	6	7	8	9	10	11	11	11	11
LE	4	6	6	6	6	7	8	9	10	11	11	11
+	5	6	6	6	6	6	7	8	9	10	11	11
ΔLE	6	6	6	6	6	6	6	7	8	9	10	11
+	7	6	6	6	6	6	5	6	7	8	9	10
LE	8	6	6	6	6	5	4	5	6	7	8	9
	9	6	6	6	5	4	3	4	5	6	7	8
	10	6	6	5	4	3	2	3	4	5	6	7
	11	6	5	4	3	2	1	2	3	4	5	6

4. Simulation Experiments and Comparisons with Proportional Integral Controllers

For the high power case, we have run two simulation experiments for this study ; the first is the case of full power normal operation with one of the three running pumps being tripped(Fig.11), and the second is the case of 50% nuclear power with one of the two running pumps being tripped(Fig.12).

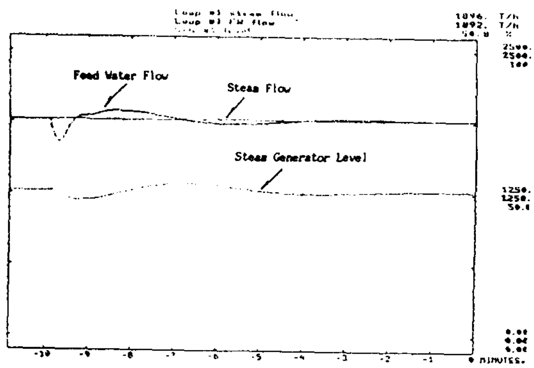

Fig. 11. Simulation Results for the Case of Full Power (PI Controllers)

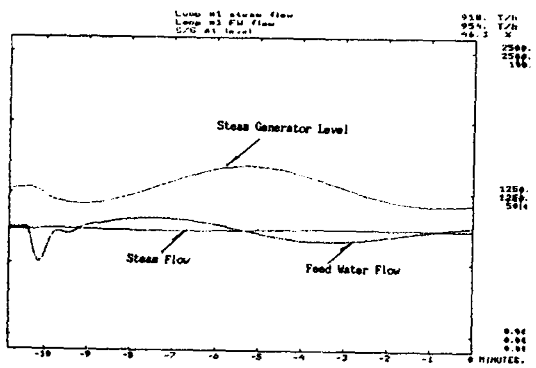

Fig. 12 Simulation Results for the case of 50% nuclear power (PI Controller)

We also have run two more simulation experiments with the fuzzy logic controller for the high power case. These are actually simulation operations for the low power case. The first is the case of reducing the generator power from 100MWe to 50 MWe with the load rate of 5MWe/min while the nuclear power is held at 16.8%. The second is the case of increasing the generator power from 0 MWe to 100MWe while the nuclear power is held at 12%.

Note that in both of these low power operation experiments, the steam dump valve must open and close periodically to dump out the excess steam and hence the swell and shrink effects must occur. Assuming that the data for the steam flow and the feedwater flow are available, the fuzzy logic controller for the high power case can be used for the level control.

Thus, we have run altogether a set of four simulation experiments for the high power case. For the first two experiments, the simulation results are as shown in Fig.13 and Fig.14 respectively.

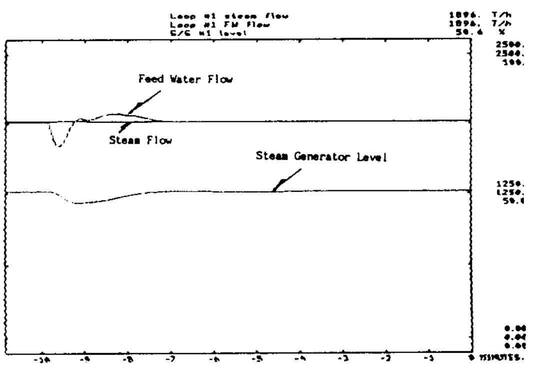

Fig. 13. Simulation Results for the Case of Full Power (Fuzzy Logic Controller)

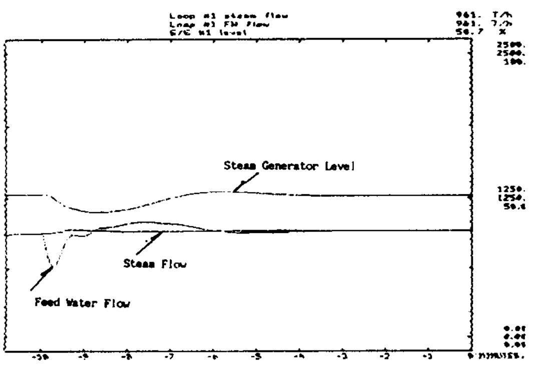

Fig. 14. Simulation Results for the Case of 50% Power (Fuzzy Logic Controller)

Note that the overshooting effects shown in the level curves of in Fig.11 and Fig.12 are nearly eliminated in Fig.13 and Fig.14. This fact is well described by the total variation of the level error curve in Table 6.

Table 6. Comparision of Total Variation of Curves (High Power Case)

Generator Power Change	Controller	Control Action (%/100)	Level Error (%/100)	Flow Error
Full	Fuzzy	0.3252	0.0757	151.4
Power	PI	0.6592	0.2691	338.4
50%	Fuzzy	0.6107	0.1366	207.9
Power	PI	1.2140	0.6868	594.8
10%	Fuzzy	0.3721	0.5099	164.1
to 5%	PI	1.2720	1.0270	473.5
0%	Fuzzy	0.4364	0.7915	288.7
to 10%	PI	1.6550	1.5880	877.4

The numbers in Table 6 represent the total variation of various curves, where the units are the percentage points divided by one hundred for the first two curves and tons/hour with a division factor of 0.278 for the flow error curve. All of these are run during a period of about 11 minutes of simulation with five times the real time run mode.

We see that each of the computed values for the total variation by the fuzzy logic controller is less than one half of the coppesponding value for the PI controller.

To see the difference between the PI controller and the fuzzy logic controller, we computed the analytic equivalents. For the PI controller, we compute from Fig.1 by a simple algebra that

$$U(t)=3.3e(t)+0.33\int_0^t e(t)dt$$
$$+0.5\times10^{-5}\int_0^t f(t)dt+0.1\times10^{-3}f(f)$$
$$+9.25\times10^{-5}\int_0^t\int_0^t e(t)dt \qquad (1)$$

where

e(t) : Level Error (the actual level–the set point),

$f(t)$: Flow Error (the feedwater flow–team flow),
$u(t)$: the controller output.

For the fuzzy logic controller, we compute linear functions in two variables from Tables 1 and 2. Note that in the tables, the set numbers 1 through 7 for LE and for LE+ΔLE are identified with the corresponding x–coordinates in Fig.4, the fuzzy set numbers 1 through 9 of ΔLE are identified with those in Fig.5, and similarly for the flow error and for the controller output with Fig.6 and Fig.7 respectively. Now, the two tables can be viewed as representing some functions in two variables. We assumed they are linear functions in two variables and applied the least squares method to obtain

$$\Delta u(t) = 0.84397\Delta e(t) + 0.05291 e(t) + 2.985\times 10^{-4} f(t). \qquad (2)$$

where

$\Delta e(t)$: increament of $e(t)$.

The equation (2) represents our final level controller for the high power case where its performance is identical to that of the fuzzy logic controller.

For the low power case, we have conducted a pair of runs for each of the two simulation experiments described above. One of the runs is with a constant level set point at 50% and the other is with the variable level set point that varies from 40% to 50% as the nuclear power varies from 0% to 20%(Fig.15).

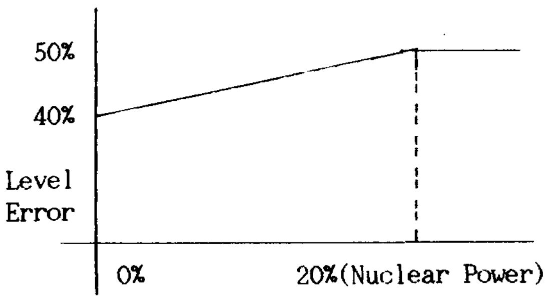

Fig. 15. Variable Set Point

We see from Fig.16 and Fig.17 that the level experiences the swell and shrink effects. By comparing with the results of the PI controller, we find that much of the overshooting effect is reduced in this case also. The total variation of the level error in Table 7 reflects this fact very well.

Table 7. Comparision of Total Variation of Curves (Low Power Case)

Generator Power Change	Set Point	Controller	Control Action	Level Error	Flow Error
10% to 5%	Constant	Fuzzy	0.772	1.109	397.8
		PI	2.093	2.083	1054.0
	Variable	Fuzzy	0.853	1.067	390.6
		PI	2.197	2.196	1057.0
0% to 10%	Constant	Fuzzy	0.926	1.474	588.5
		PI	2.944	2.928	1439.0
	Variable	Fuzzy	1.048	1.444	593.4
		PI	2.941	2.958	1453.0

Note that all of the values for the total variation of curves by the fuzzy logic controller are less than or around one half of those by the PI controller. The analytic equivalent of the PI controller is computed from Fig.2 as follows;

$$u(t) = 2.0e(t) + 2.67\times 10^{-3}\int^{t} e(t)dt \qquad (3)$$

An equivalent analytic form for the fuzzy logic controller for the low power case is obtained from table 3, 4 and 5 as follows;

$$e^{*}(t) = F\{\Delta e(t), \int_{o}^{t} e(t)\}$$
$$= 19.88\Delta e(t) + 1.388\times 10^{-3}\int_{o}^{t} e(t)dt$$
$$e(t) = G\{e(t), e^{*}(t)\}$$
$$= 0.5380e(t) + 0.7686e^{*}(t)$$
$$= 0.5374e(t) + 0.7653\{19.88\Delta e(t) + 1.388\times 10^{-3}\int_{o}^{t} e(t)dt\} \qquad (4)$$
$$u(t) = H\{e(t), \Delta T_{ref}\}$$
$$= -4.4333e^{2}(t) - 393.7e(t)\Delta T_{ref} + 347.6(\Delta T_{red})^{2} - 13.09e(t) + 7.306\Delta T_{ref}$$

where

F(x,y) : the function of two variables in table 3,

G(x,y) : the function of two variables in table 4,

H(x,y) : the function of two variables in table 5.

Note that the function H in (4) is a quadraric function. Since the function in Table 5 is non-linear, we have chosen a quadratic function for the curve fitting. The equation(4) represents our final level controller for the low power case which is nearly identical to the fuzzy logic controller.

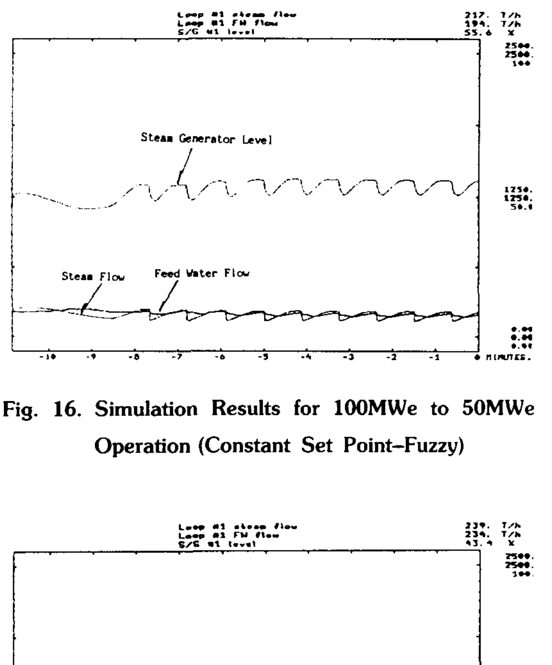

Fig. 16. Simulation Results for 100MWe to 50MWe Operation (Constant Set Point-Fuzzy)

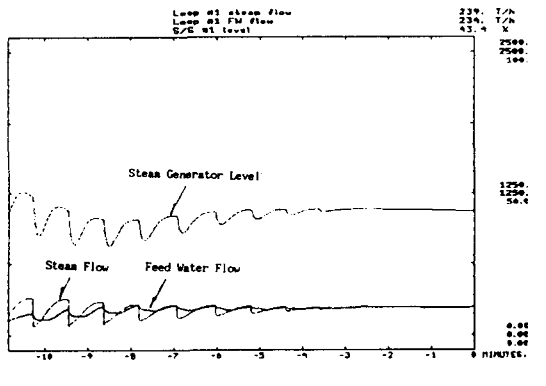

Fig. 17. Simulation Results for 0 to 100Mwe Operation (Variable Set Point-Fuzzy)

5. Conclusions and Remarks

The level controllers we have developed through a set of fuzzy algorithms are found to behave better than the PI controllers in terms of the total variations of the level error, the flow error, and of the control action.

For the high power case, the total variations including that of the control action are about one half of those by the PI controller. The difference is essentially due to the fact that we use the velocity algorithm on PD controllers, i.e. $\Delta u = \alpha LE + \beta \Delta LE$ while PI is $u = \beta LE + \alpha \int LE$ for some constants α and β, and hence almost all of the overshooting effect is eliminated. Note also that by using the derivative of the level error, one can somehow forecast the trend of the level error curve while the integral reflects a history of the level error curve.

For the low power case, the major part of our controller is also a PD type controller rather than a PI controller. The irregular changes in the derivative of the level error and in the controller output have been handled properly by taking the averages over a certain period of time. The total variations of the level error, of the flow error and of the control action are also about one half of those by the PI controller.

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