Hybrid Feedforward and Feedback Controller Design for Nuclear Steam Generators over Wide Range Operation Using Genetic Algorithm

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***Abstract*—In this paper, a simplified model with a lower order is first developed for a nuclear steam generator system and verified against some realistic environments. Based on this simplified model, a hybrid multi-input and multi-out (MIMO) control system, consisting of feedforward control (FFC) and feedback control (FBC), is designed for wide range conditions by using the genetic algorithm (GA) technique. The FFC control, obtained by the GA optimization method, injects an *a priori* command input into the system to achieve an optimal performance for the designed system, while the GA-based FBC control provides the necessary compensation for any disturbances or uncertainties in a real steam generator. The FBC control is an optimal design of a PI-based control system which would be more acceptable for industrial practices and power plant control system upgrades. The designed hybrid MIMO FFC/FBC control system is first applied to the simplified model and then to a more complicated model with a higher order which is used as a substitute of the real system to test the efficacy of the designed control system. Results from computer simulations show that the designed GA-based hybrid MIMO FFC/FBC control can achieve good responses and robust performances. Hence, it can be considered as a viable alternative to the current control system upgrade.**

I. INTRODUCTION

Recently many application studies[1-3] on advanced control techniques, such as robust control, neural networks, etc., have been undertaken, both theoretically and experimentally, in the field of nuclear power industry. However, most of these investigations have some of the following limitations:

(1) Narrow operating conditions, usually around the rated nominal power, have been used for the studies. There are many wide range operations, such as, start-up, shut-down, large load changes, etc., existing in the nuclear power plants. Currently, the nuclear power industry relies heavily on the manual operations for those wide range operations. But, human errors in such wide operations can be costly and disastrous[4-5]. Additionally, it is well known that a reliable automatic control is deemed a necessary condition which optimizes thermal stress, minimizes material fatigue, reduces the number of staff, and enables efficient plant operations.

(2) Both linearized models and frequency design techniques are utilized to design the control system. But, the real power system is a highly nonlinear and complicated system.

(3) The resulting control system is usually too complicated or have too high order to be acceptable for industrial implementation.

Hence, with these limitations of various control alternatives and risks from upgrading the existing control system, the PID-based conventional control systems are still widely implemented in the power and other industries and also incorporated in the upgrades of power plant instrumentation and control (I&C) systems. However, the current PID-based conventional control systems do not have the flexibility necessary to provide good safety and economic performances over a wide range of operations although they can generally yield an acceptable responses for the designed conditions. Therefore, it is highly necessary and desirable to design a control system which not only can improve the nuclear power plant safety and economic performance, but also is more acceptable to the nuclear power utility when implemented for a wide range of operating conditions.

Based on these facts and observations, a control system, combining FFC with FBC, is presented in this paper to tackle some of the problems. This approach does not need to overhaul existing control systems while incorporating advanced control technology to improve their performances. This hybrid control system is deigned via the genetic algorithm (GA) technique which is a global search optimization method and recently finds more and more applications in power and other fields[6-7].

The designed control system is applied to a nuclear steam generator which is a critical component in a pressurized water reactor (PWR) power plant. The steam generator connects the primary system with the secondary in the PWR plant and its safe operation plays a very important role in the overall safety of the PWR power plant. The steam generator is also an excellent example to be used to test the designed

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control system because it is a highly nonlinear and complex system in which many complicated phenomena occur.

The remainder of this paper is organized as follows: In Section 2 a model of the steam generator system is developed for the design of the control system. Section 3 first gives an overview of the GA technique and then the mechanism of the GA-based MIMO hybrid FFC/FBC control system is presented. Some application results from computer simulations are included in Section 4. Section 5 presents some concluding remarks and future research.

II. MODELING OF STEAM GENERATOR SYSTEMS

There are generally two types of steam generators: The U-type and the once-through steam generator (OTSG) in the nuclear power industry. The steam generator, a crucial part in the PWR power plant, connects the primary side with the secondary[8].

The OTSG system, as shown in Fig. 1, is a Babcock & Wilcox (B&W) type with a steam aspiration or circulation port to preheat the incoming feedwater. It is a counterflow vertical heat exchanger. The primary fluid, reactor coolant, flows downward through the inside of the tubes. The secondary fluid, feedwater and steam, flows upward in the outside of the tubes. The feedwater enters the OTSG as subcooled liquid; in its path, it boils and leaves as superheated vapor at the top. While under normal operating conditions the primary side is single phase (fluid) flow, the secondary undergoes an entire spectrum of flow regimes.

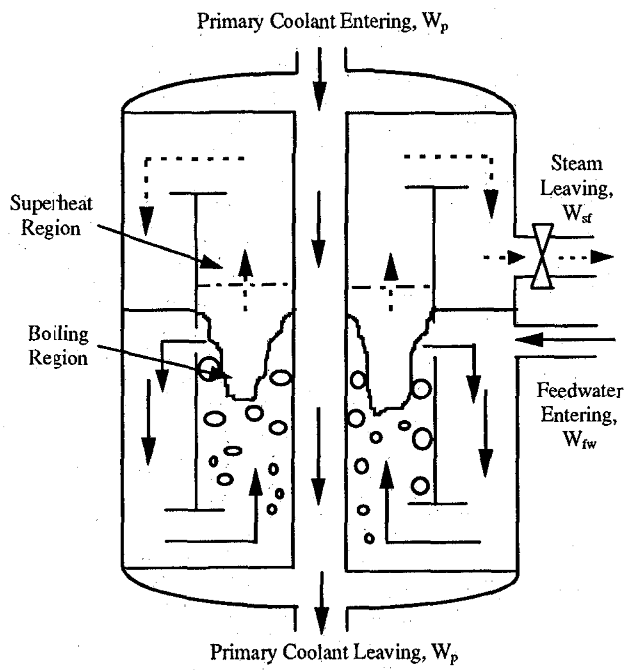

Fig. 1. Schematic of OTSG System

It is quite necessary to make the modeling as simple as possible to limit the size of the design problem, reduce the computation time and yet retain adequate dynamic information for the hybrid FFC/FBC control system design to achieve its goal of improving plant operations.

The OTSG model consists of the following six differential equations, and has two inputs (feedwater flow rate W_{fw} and steam valve position Y) and two outputs (water level L and steam flow rate W_{sf}). The detailed derivation of this model can be found in [9].

$$\frac{dL}{dt} = \frac{1}{3600 A_s \rho_{s1}} [W_{fw} - \frac{\dot{q}_1}{\Delta h_{e,sat}}] \quad (1)$$

$$\frac{dP_{s2}}{dt} = \frac{1}{\alpha_{P_{s2}}} (\frac{\dot{m}_2 - W_{sf}}{3600 V_{s2}} + \frac{\rho_{s2}}{(H-L)} \frac{dL}{dt} - \alpha_{h_{s2}} \frac{dh_{s2}}{dt}) \quad (2)$$

$$\frac{dh_{s1}}{dt} = \frac{1}{\rho_{s1} V_{s1}} [\frac{\dot{q}_1 + W_{fw} h_{se} - \dot{q}_1 h_{sat} / \Delta h_{e,sat}}{3600} - \rho_{s1} h_{s1} A_s \frac{dL}{dt} + \frac{144}{778} A_s L \frac{dP_{s1}}{dt}] \quad (3)$$

$$\frac{dh_{s2}}{dt} = [\frac{\dot{q}_2 + \dot{q}_1 h_{sat} / \Delta h_{e,sat} - h_{s2} W_{sf}}{3600} + \rho_{s2} A_s h_{s2} \frac{dL}{dt} - h_{s2} V_{s2} \frac{d\rho_{s2}}{dt} + \frac{144}{778} V_{s2} \frac{dP_{s2}}{dt}] \frac{1}{\rho_{s2} V_{s2}} \quad (4)$$

$$\frac{dh_{p1}}{dt} = \frac{W_p (h_{p2} - h_{p1}) - \dot{q}_1}{3600 \rho_{p1} A_p L} \quad (5)$$

$$\frac{dh_{p2}}{dt} = \frac{W_p (h_{pe} - h_{p2}) - \dot{q}_2}{3600 \rho_{p2} A_p (H-L)} \quad (6)$$

where P_{s2} is the steam pressure in the superheated region, h_{s1} and h_{s2} are the average enthalpy of fluid in the boiling and superheat region, respectively, of the secondary side, and h_{p1} and h_{p2} are the average enthalpy of fluid corresponding to the primary side boiling and superheat region, respectively.

The heat transfer used in the development of the above steam generator model is represented as follows: For the boiling region, the heat, transferred from the primary coolant to heat the entering feedwater, is modeled as

$$\dot{q}_1 = P_m L U_{p1,s1} (T_{p1} - T_{s1}) \quad (7)$$

where P_m is the wetted perimeter, $U_{p1,s1}$ is the average heat transfer coefficient between the primary coolant and the feedwater on the secondary side, T_{p1} and T_{s1} are the average temperature of fluid on the primary and secondary side, respectively, in the boiling region.

For the region of superheat, the heat is transferred from the entering primary coolant to superheat the steam on the secondary side which is produced from the boiling region, and similarly it can be represented as below:

$$\dot{q}_2 = P_m (H-L) U_{p2,s2} (T_{p2} - T_{s2}) \quad (8)$$

where H is the total tube length of the steam generator, $U_{p2,s2}$ is the average heat transfer coefficient between the primary coolant and the steam on the secondary side, T_{p2} and T_{s2} are the average temperature of coolant on the primary side and steam on the secondary side, respectively, in the superheat region.

The model for the steam controlling valve is given below:

$$W_{sf} = YC_{v\max}[1-0.33(\frac{X_x}{0.9X_T})]\sqrt{\rho_{s2}X_xP_{s2}} \quad (9)$$

where C_{vmax} is maximum steam valve conductance, X_T is maximum pressure loss ratio for the valve at which choking occurs, and X_x is pressure loss ratio.

This simplified model is compared with the corresponding B&W Modular Modeling System (MMS) OTSG model which, with a tenth order, has been widely used in the power plant simulation. Two representative results of comparisons are given in Figs. 2 and 3 which are the responses to a +10% step change in the primary coolant flow rate at the time of 50 seconds.

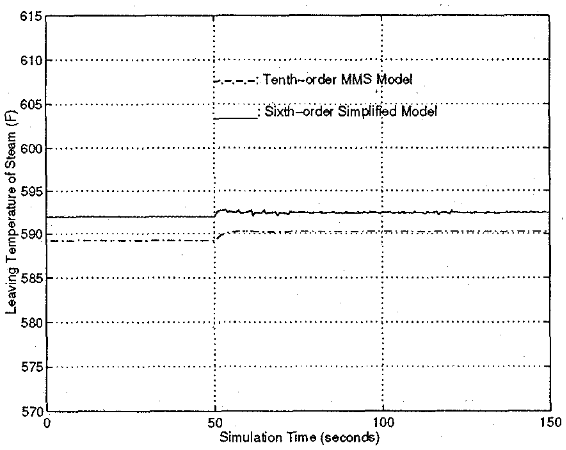

Fig. 2. Step Change Response of Leaving Coolant Temperature

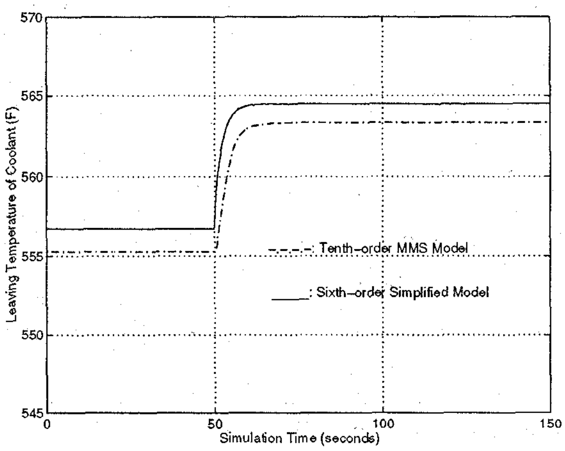

Fig. 3. Step Change Response of Leaving Steam Temperature

It can be concluded from the comparisons, as shown in Figs. 2 and 3, that the simplified OTSG model approximates the MMS model quite well and hence is a candidate for designing control systems.

III. HYBRID FEEDFORWARD/FEEDBACK CONTROL USING GA TECHNIQUE

A. Overview of Genetic Algorithm

The genetic algorithm is a parallel, global probabilistic search technique based on the principle of population genetics. Generally, the genetic algorithm technique consists of four steps which can be concisely explained as follows[10-11]:

1) Encoding and Initialization

This first step needs to encode the parameters or solution space and initialize the population of the first generation.

- *Coding*: Before we use the genetic algorithm for designing a control system, we have to encode the solution space using a suitable representation scheme. It is standard to translate the parameters into binary bit strings, that is, strings of 1's and 0's. Such strings can be lengthened to provide more resolution for the parameter representation. Using this scheme of representation, various components of a solution are represented by binary strings that are then concatenated to form a single binary string called a chromosome. Additionally, there are some forms of representations as well. For simplicity, we will use the binary representation in this paper.
- *Initialization of Population*: Once a suitable representation has been selected, the next step is to initialize the population. This is usually done by a random generation of binary strings representing the chromosomes. A uniform representation of the solution space is ensured this way.

2) Selection Process

This second step in the GA provides a measure of fitness for each candidate solution for the given problem.

- *Fitness evaluation*: The strings in the current generation are decoded to be their decimal equivalents. Then, they are judged with some objective functions and assigned individually with fitness values.

3) Genetic Operations

There are three fundamental operators in this process which includes reproduction, crossover, and mutation.

- *Reproduction Operation*: The strings with larger fitness values can produce with higher probability a larger number of their copies in the new generation by the reproduction operation. In the elitist reproduction, the current best string is guaranteed a long life from generation to generation by making one of its copy directly into the next generation. The reproduced strings are placed in *a mating pool* for further use.
- *Crossover Operation:* The strings can exchange information in a probabilistic way by the crossover operation. Two strings are chosen from the mating pool and arranged to exchange their corresponding portions of the binary strings at a randomly selected position along them.

This process can combine good qualities among the preferred strings.

- *Mutation Operation*: The strings can change their structure abruptly by the mutation operation through an occasional alternation of a value at a randomly selected bit position along them. The mutation process may quickly generate those strings which might not be conveniently produced by the reproduction and crossover operations. Since it may also spoil the opportunity of the appropriate generation, mutation usually occurs with a small probability.

4) Iteration Process

Steps (2) and (3) usually need to be iterated before the final global optimal solution is found.

- *Iterative Process:* The genetic algorithm runs iteratively repeating the process until it arrives at a predetermined ending condition. Finally, the acceptable solution is obtained and decoded into its original pattern.

B. GA-Based Hybrid FFC/FBC Control

The general configuration for this hybrid FFC/FBC control is illustrated in Fig. 4. The FFC control (u_{ff}) is used to exercise planned control based on the designated references and model while achieving optimal performances if the system can be maintained close to the designed model. The FBC control (u_{fb}) is employed to provide the necessary compensation against any disturbances or uncertainties in the actual system.

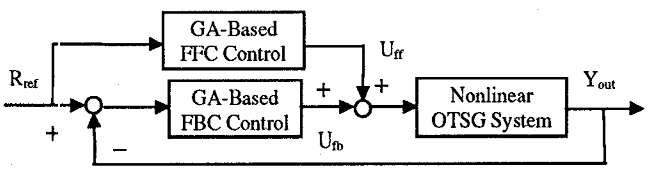

Fig. 4 Configuration of Hybrid FFC/FBC Control

The structure of this GA-based FBC control can be shown in Fig. 5. The FBC control, used in this paper, is an optimal design of the PI-based control with the cross-coupling effects considered. Hence, parameters need to be trained by the GA are two integral, proportional, and cross-coupling gains.

The six parameters, as shown in Fig. 5, are trained by the GA by adding additional parameters sequentially in the following four stages[7]:

- First training stage: K_{p1} and $K_{p2.}$
- Secondary training stage: K_{I1} and $K_{I2.}$
- Third training stage: $K_{12.}$
- Fourth training stage: $K_{21.}$

The quadratic performance objective function (J) and the fitness function (f), used in this paper, are given below:

$$J = \int_{T_o}^{T_{ref}} \left\{ 100(L - L_{ref})^2 + 0.2(W_{sf} - W_{ref}(t))^2 \right\} dt \qquad (10)$$

$$f = \frac{1}{(1+J)}. \qquad (11)$$

where L is the output of the water level, W_{sf} is the steam flow leaving the steam generator, and subscripts *ref* and *sf* denote reference and steam flow, respectively.

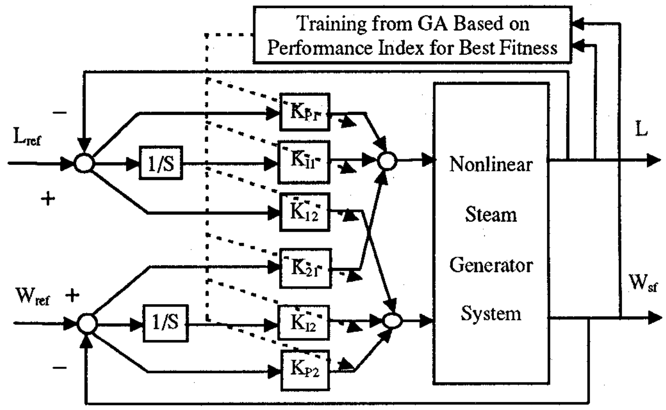

Fig. 5. Diagram of GA-Based FBC Control for Steam Generator System

C. GA-Based FFC Control

The FFC control (u_{ff}) is implemented to provide the predictive command input to the system based on the designated performances and the simplified steam generator model. The FFC control (u_{ff}) can be obtained by training the reference u_{ref} through the following ramp function:

$$u_{ff}(t) = u_0 + \frac{(u_{ref} - u_0)}{T_{ref} - T_0} t, \qquad (12)$$

where T_0 is the time at which the simulation starts, T_{ref} is the final time of the ramp function, u_0,, chosen randomly at the beginning the simulation, is the initial FFC control (u_{ff}) which includes the feedwater flow rate (W_{fw}) entering the steam generator system and the steam controlling valve position (Y).

IV. SIMULATION RESULTS AND ANALYSES

The two training signals are the steam flow and water level. The steam flow is trained from 1458.3lbm/s to 729.2lbm/s linearly while the water level is trained to be constant at 21.15ft. The Computer simulations are first carried out on the simplified OTSG model. And then the MMS OTSG model, which has a higher order and much more complicated than the simplified model, is used as an actual OTSG system to test the efficacy of the GA-based hybrid FFC and FBC control. As a prototype experiment, the wide range operation is to ramp the steam flow rate (i.e., thermal power) from 100% down to 50% within 20 seconds while keeping the OTSG water level as constant as possible. After 20 seconds, the system operation is steadily maintained at the 50% power level.

A. Application to the Simplified OTSG Model

The PI-based FBC control designed via the GA technique is first tested on the simplified model. The computer simulation results are shown in Figs. 6 and 7 for the control of the wide range of operation designated above.

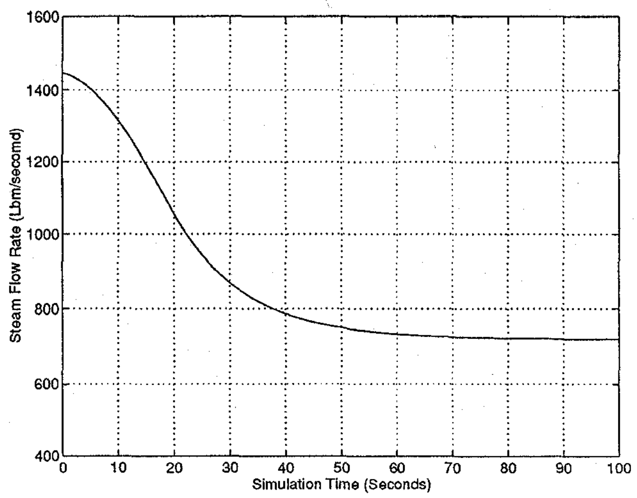

Fig. 6. Response of Steam Flow Leaving OTSG

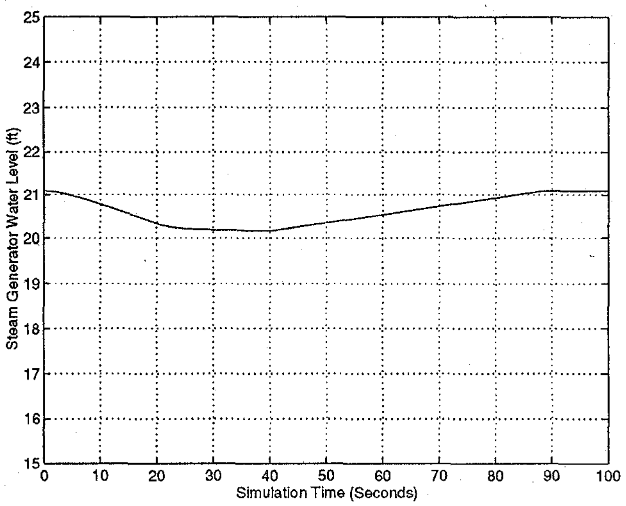

Fig. 7. Response of OTSG Water Level

Simulation results given in Figs. 6 and 7 show that the GA-based PI control achieved quite good performances. For the purpose of comparison, the hybrid GA-based FFC/FBC control is also applied to the same simplified model. The computer simulation results are shown in Figs. 8 and 9.

It can be seen from Figs. 8 and 9 that the responses of the two outputs are much better than those obtained by the FBC control alone. The improvement of responses is attributed to the function of the GA-based FFC control. Such good performances shown in Figs. 8 and 9 are also anticipated because the control scheme is designed and optimized via the GA technique based on the model on which the application is conducted.

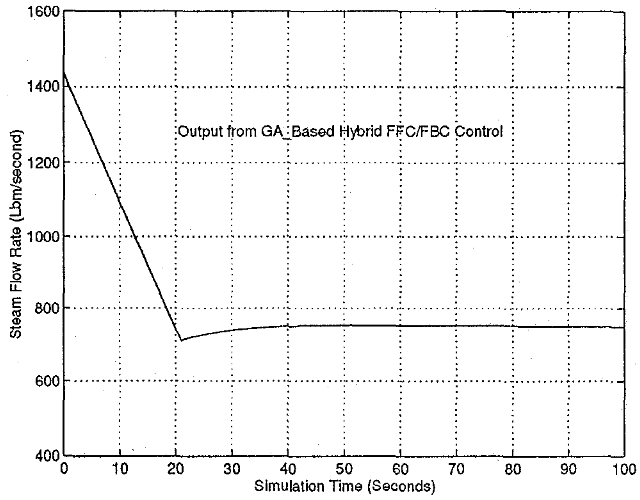

Fig. 8. Response of Steam Flow Leaving OTSG

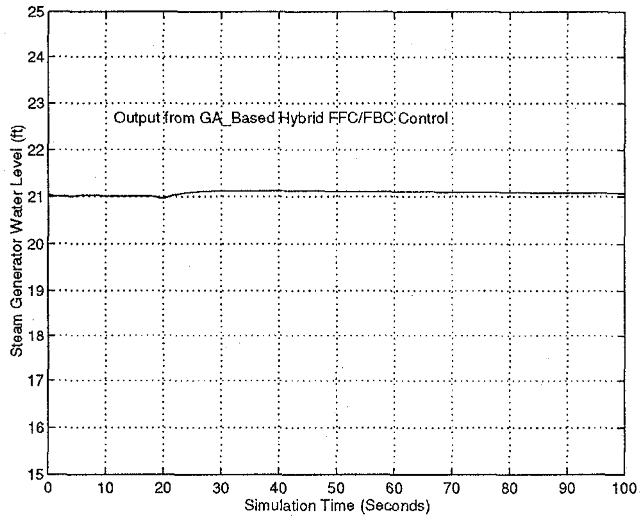

Fig. 9. Response of OTSG Water Level

B. Application to the MMS OTSG Model

The MMS OTSG model has a higher order and is more complicated than the simplified model which is utilized to design the GA-based MIMO FFC/FBC control. This MMS model is used in this paper as a substitute of the real OTSG system to verify the efficacy of the designed control system. There exist some dynamic differences between these two models. For the same wide range operation as mentioned above, the simulation results from this application are given in Figs. 10 and 11.

Results shown in Figs. 10 and 11 demonstrate that the responses of the two outputs are quite satisfactory although the performance is not as good as that of the application to the simplified model.

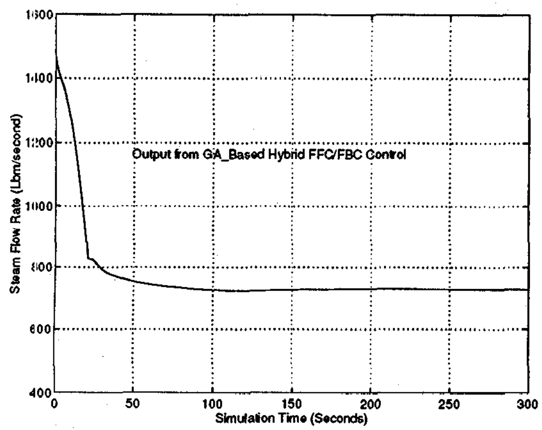

Fig. 10. Response of Steam Flow Leaving OTSG

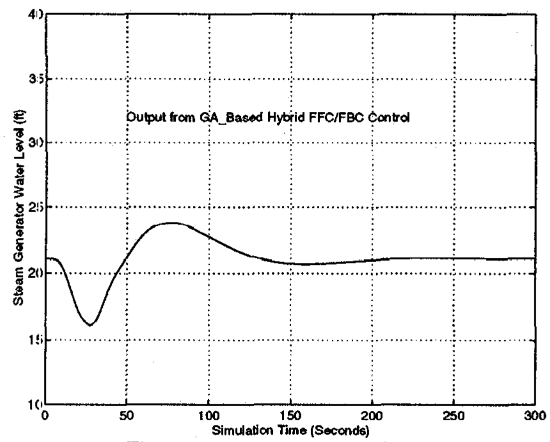

Fig. 11. Response of OTSG Water Level

V. CONCLUSIONS AND FUTURE RESEARCH

In this paper, a MIMO GA-based hybrid control system, consisting of FFC/FBC, is presented for a nuclear steam generator system over a wide range of operations. The FFC control is obtained by the global GA optimization technique and the FBC control is an optimal design of the PI-Based control system. A sixth-order nonlinear MIMO model is developed for the steam generator system and its accuracy has been validated. Some good application results from computer simulations are achieved which manifest the efficiency and effectiveness of the designed MIMO FFC/FBC control system using the GA method. This research can be expanded to cover a whole power plant system, and the proposed hybrid MIMO hybrid FFC/FBC control system applied to both a simplified plant-wide model and a real power plant system.

VI. ACKNOWLEDGMENT

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BIOGRAPHIES

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