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Brief Paper

Fuzzy wide-range control of fossil power plants for life extension and robust performance☆

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Abstract

This paper presents a fuzzy-logic-based methodology of life extending control (LEC) for robust wide-range operation of fossil power plants including load-following, scheduled shutdown, and hot startup. The objectives of the LEC are performance enhancement and structural durability of both aging and new fossil power plants. The proposed control system has a two-tier architecture, which explores and optimizes the plant performance and structural durability trade-off. The lower tier consists of a feedforward control policy and a family of linear multivariable robust feedback controllers, which are gain-scheduled for wide-range operation. The sampled-data feedback control laws are synthesized based on an induced L_2-norm technique that minimizes the worst-case gain between the energy of the exogenous inputs and the energy of the regulated outputs. The supervisory controller at the upper tier makes decisions on plant operations with due consideration to structural durability of critical plant components (e.g., steam generators, steam headers, and turbines). The supervisory controller is synthesized based on approximate reasoning embedded with rule-based expert knowledge of the power plant and analytical models of structural damage. Using the fuzzy logic, the plant operation strategy is modified on-line for trade-off between plant performance and structural damage in critical components. The fuzzy algorithm facilitates *bumpless* controller switching for gain scheduling under wide-range operation and control. It also adds robustness to the control system especially if the lower tier of gain-scheduled controllers is not able to maintain stability under plant perturbations.

Keywords: Power plant control; Life extending control; Robust control; Gain scheduling; Fuzzy control

1. Introduction

Life extending control (LEC) is a field of research involving the integration of two distinct disciplines: *System Sciences* and *Mechanics of Materials*. The objectives of LEC are performance enhancement and structural durability of both aging and new plants. Ray, Wu, Carpino and Lorenzo (1994) have shown that, using optimal open-loop feedforward control sequences, it is possible to substantially reduce the damage in an explicit manner without any significant reduction of dynamic performance. The concept of LEC has been later extended by several researchers including Kallappa, Holmes and Ray (1997), Tangirala, Holmes, Ray and Carpino (1998), and Holmes and Ray (1998) for robust feedforward-feedback control. This paper is a sequel to the earlier publication (Kallappa et al., 1997) where feedforward control policies are generated via extensive off-line optimization to achieve high performance and life extension of fossil power plants. Each feedforward policy is synthesized as a finite sequence of open-loop control inputs via constrained optimization under transient operations. The optimization process uses plant and damage models (which are complex and often computationally intensive) and the cost functional consists of performance and damage criteria. This control methodology is tested for life extension of a single plant component, namely, the main steam header, because inclusion of other critical components into the optimization process significantly increases the computation time to achieve convergence. The present paper develops a procedure for synthesis of output feedback laws for life extending control in which reduction of structural damage to several plant

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components is implicitly considered. It focuses on life extension of steam generator tubes, main steam header, and hot reheat header that are the most critical components in a fossil power plant (Electric Power Research Institute, 1988). The major contributions of the present paper beyond what is reported in the previous publication (Kallappa et al., 1997) are summarized below:

- The plant operating range under load maneuvering is extended down to 25% rated power in the present control system in contrast to 40% rated power in the earlier one. Since the plant dynamics are relatively much more nonlinear in the 40–25% range, a bank of robust linear feedback controllers is introduced instead of a single controller. This, in turn, requires gain scheduling leading to on-line controller reconfiguration. The fuzzy supervisory controller allows bumpless switching of controllers to ensure both dynamic performance and structural durability as well as provides stability under gain scheduling.
- The present control system follows a two-tier architecture where the supervisory control law makes *intelligent* decisions for wide-range load maneuvering with a trade-off between plant performance and structural durability of several critical components. The concept of a fuzzy control law for controller switching and structural durability in power plants has not been reported elsewhere to the best of the authors' knowledge. A typical example of the reported work in fuzzy control of power systems stability is to maintain the generated load frequency and voltage constant in the presence of varying demand (Jamshidi, Vadiee & Ross, 1993).
- The present control system is more flexible than the earlier one in the sense that operational maneuvers are not assumed to be known a priori. Therefore, load regulation can be remotely exercised without an explicit knowledge of the initial and target states.
- The present control system simultaneously regulates structural damage in several plant components in contrast to the earlier one, which is limited to a single plant component due to complexity of optimization of the feedforward signal.

2. Wide range life extending control system

The life extending control (LEC) system is designed for wide range (i.e., 25–100% rated power) operations of fossil-fuel steam power plants via damage mitigation in the critical power plant components whose failure may force unscheduled plant shutdown. This paper focuses on structural durability of radiant superheater tubes of the steam generator, and main steam header, and hot reheat steam header as they together constitute the largest source of failures (due to creep-fatigue interaction) in fossil-fuel power plants (Electronic Power Research Institute, 1988).

The LEC system synthesis is carried out based on the dynamic models of: the power plant under control and structural damage in critical components. The details of plant dynamic model are reported by Weng, Ray and Dai (1996). The plant model is a finite-dimensional state-space representation having 27 states, 4 inputs and 4 outputs. The plant inputs that are actuator commands, and the plant outputs that are sensor signals for the feedback control system, are listed in Table 1. Some of the plant outputs in Table 1 along with additional sensor signals are inputs to the component structural model that generates the necessary information for the damage prediction model. The output of the damage model is the damage vector that consists of changes in shape, size, crack lengths and geometry of components. For example, for superheater tubes, reduction in tube thickness due to creep flow is an element in the damage vector. The damage models for the main steam header and hot reheat header have been derived by Kallappa et al. (1997) and the damage model for the superheater tubes by Lele, Ray and Kallappa (1996).

The onus of damage mitigation is on feedback, but feedback alone is not capable of sustaining the plant stability and performance for the nonlinear plant for wide range operation. Since the role of linear feedback controllers is to reduce deviations from nominal trajectories, a family of controllers is designed to locally regulate the plant at a series of operating points. It is therefore logical to use a *static* feedforward sequence that is formulated based on steady-state plant conditions and increment with robust feedback control. In contrast to (optimized) dynamic feedforward control reported earlier

Table 1
List of plant input and output variables

#	Input variables	Symbol	Unit	Output variables	Symbol	Unit
1	Governor valve area	AGV	—	Throttle steam temperature	TTS	°F(°C)
2	Feedpump turbine valve area	APT	—	Hot reheat steam temperature	THR	°F(°C)
3	Fuel/air valve area	AFA	—	Throttle steam pressure	PTS	psi (MPa)
4	Attemperator valve area	AAT	—	Electrical power	JGN	MW

by Kallappa et al. (1997), this static feedforward control policy is obtained as an algebraic function of certain measured plant outputs.

In the wide range of operation from 25 to 100% of full load, a single linear feedback controller may not yield the required robustness for performance and stability especially in the range below 40% where the power plant dynamics are increasingly nonlinear (Weng et al., 1996). Specifically, a single controller, designed on a given linearized plant model, may not meet the stability and performance requirements while operating away from the equilibrium point of linearization. Furthermore, structural damage in plant critical components will significantly increase due to large oscillations in the plant states. Analogous to plant stability and performance, the damage mitigation quality of a control system may not be effective away from the postulated region of plant operation. Therefore, a viable option for LEC is gain scheduling that is commonly used for wide range control of complex dynamical processes such as power plants and tactical aircraft (Nichols, Reichart & Rugh, 1993).

We propose a new approach to supervisory control in which gain scheduling is supplemented with fuzzy control to ensure robust stability while achieving high dynamic performance and extended life over a wide range of power plant operations. Wang et al. (1996) use fuzzy logic to gain schedule a series of linear controllers for very small order systems by interpolating the outputs of linear controllers. This technique may not ensure stability for large-order dynamical systems. Due to the use of static feedforward, the combined role of supervisory control and robust feedback control reduces to locally regulating the plant at a series of operating points and mitigating structural damage in the critical components. The family of linear robust feedback controllers, under consideration, is synthesized based on induced L_2-norm techniques (Bamieh & Pearson, 1992) as reported earlier (Kallappa et al., 1997). Fig. 1 gives an overview of the wide-range control system and the control strategy is summarized as follows:

- The (static) feedforward control u^{ff} is calculated and stored, based on steady-state operating conditions from 25 to 100% plant load. In the present design, u^{ff} is calculated at 5% intervals that yields a smooth curve-fit to the data points for each element of u^{ff} with the plant load as the independent variable.
- The linear robust feedback controllers are designed at different levels of plant load to cover the entire range of plant dynamics. The supervisory controller is used to gain schedule these linear controllers based on the plant load. The concept of an observer-based bi-directional switching technique (Astrom & Wittenmark, 1984; Graebe & Ahlen, 1996) is used to switch from one controller to the other. The supervisor also uses a fuzzy-logic-based algorithm to calculate the reference trajectory y^{ref} in order to maintain stability and performance as well as to keep the damage rates low.

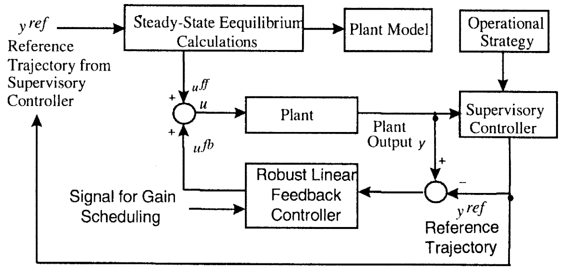

Fig. 1. Wide range life extending control system.

2.1. Supervisory controller

The hierarchically structured supervisory controller plays a central role in the robust wide-range operation of power plants for high performance and life extension. It utilizes mathematical models of plant and damage dynamics, heuristics of plant operations, and behavior of material degradation based on the knowledge derived from human experience. The supervisory functions are achieved in part, through approximate reasoning, as a fuzzy-logic-based control law (i.e., the fuzzy controller), and in part through gain scheduling of a family of linear robust controllers. The supervisor is critical for performance and life extension during transient operations (e.g., during load ramp up and down). The crucial performance goal is to track the load-following schedule as closely as possible and maintain plant stability, while the life extension goal is to keep damage rates in plant components low. To achieve these goals, the supervisory controller makes use of the available sensory information to relax or tighten the load-following schedule based on the current stability and damage-rate indicators. If these (time-dependent) indicators suggest high damage rates or instability, the load-following accuracy is compromised. Another role of the supervisor is to achieve smooth dynamic transfer between the individual controllers by using observer-based switching and the fuzzy controller. Smooth dynamic transfer is required for plant stability and damage reduction.

2.2. Linear feedback controller design

As discussed earlier the feedback control system consists of a family of linear gain scheduled controllers. Major issues in gain scheduling include the number of linear controllers, the algorithm for switching from one controller to another, the choice of the scheduling variable, and constraints on the scheduling variable. The heuristic used for maintaining stability during gain scheduling is that the scheduling variables must vary slowly and capture the nonlinearities of plant dynamics (Shamma & Athans, 1991). For control of the power plant under consideration, a scheduling variable that effectively captures the plant nonlinearities is the generated power output (i.e., the generated load in MW). Intuitively, slow variations in plant load also reduce structural damage in the critical plant components and meet the requirements for plant stability during gain scheduling.

Packard et al. (1997) have proposed the *linear parameter varying* (LPV) control technique where the linear plant dynamics are assumed to be a function of a time-varying parameter vector ρ. However, since the LPV technique solves linear matrix inequalities (LMI), a convergent solution is often difficult to find for high-order plants such as the power plant under consideration. The next best step would be to use a series of linear controllers. In choosing the number of controllers two factors (that are mutually conflicting) need to be taken into account: (i) robust stability and performance in the entire operating range for which larger the number of controllers better is the performance; and (ii) occurrence of switching transients or interpolation of control signals on the plant performance, which is reduced with a smaller number of controllers. Based on the results of extensive simulation experiments a set of three controllers is deemed appropriate for gain scheduling over the entire operating range of 25–100% plant load. The three controllers, designed for linearized plants at 25, 35 and 60% load, are found to yield the best performance and damage mitigation. The reason for using a larger number of controllers at lower operating range is increased nonlinearity of plant dynamics at lower load (Weng et al., 1996).

The controllers are designed using the sampled-data configuration similar to what is reported in the earlier publication (Kallappa et al., 1997). The three design parameters to be chosen are the input multiplicative modeling uncertainty function W_{del}, the disturbance weighting function W_{dist}, and the performance weighting function W_{p}. The (frequency-dependent) input multiplicative weighting function W_{del} and the disturbance weighting function W_{dist} are the same for the three controllers as given below:

$$W_{\mathrm{del}}(s) = 2\left(\frac{s + 0.05}{s + 1}\right), \tag{1}$$

$$W_{\mathrm{dist}}(s) = \frac{0.1}{s + 0.1}. \tag{2}$$

Eq. (1) implies that the magnitude of plant uncertainty is being estimated as 10% at low frequencies and increasing to the limit of 200% at very high frequencies. Eq. (2) is based on the assumptions that exogenous disturbances have a maximum gain of 0.1 tapering off at frequencies over 0.1 rad/s. The performance weights are chosen to be different for each of the three controllers and are based on several criteria as discussed below.

It is observed that large oscillations of steam temperature and pressure are the major sources of damage in power plant components. Large oscillations in steam temperature are also detrimental for turbine blades while pressure oscillations are much less damaging. The structural damage in steam headers is caused primarily by creep flow at high temperatures and by fatigue cracks largely due to thermal stresses. The creep phenomenon is an exponential function of temperature and rapid temperature oscillations cause high thermal stresses and stress oscillations. On the other hand, unlike an exponential function, mechanical stress cycling induced by pressure oscillations is governed by a relatively mild nonlinear relationship. Therefore, the weight on steam pressure is relaxed to enhance the quality of load-following performance. Since the dominant modes of thermal-hydraulic oscillations in a power plant are expected to be below 10 rad/s (Weng et al., 1996), the amplitude of high-frequency oscillations (e.g., in the order of 10^2 rad/s or higher) of any output variables is likely to be insignificant. Therefore, larger penalty is imposed on lower frequencies of each performance weighting function. However, due to unmodeled dynamics, the risk of completely ignoring high-frequency oscillations is nonnegligible because, rare as they might be, these transients can cause instability leading to catastrophic failures or unscheduled plant shutdown. Based on the above observations, each performance weight is formulated as a linear combination of a low-pass filter and an all-pass filter.

The main steam generator is the major source of thermal-hydraulic instability in sub-critical power plants where rapid variations in the length of the evaporator (e.g., two-phase water/steam region under subcritical conditions) section may occur due to fluctuations in steam/water flow and rates of heat absorption. Any variations in the evaporator length are reflected in the throttle steam temperature (TTS) that is most significant of the damage-causing variables. Therefore, the penalty imposed on TTS is the largest. The performance weights of the output variables, listed in Table 1, for the controller at 60% plant load are selected as follows:

$$W_{p1}(s) = 20 + \frac{100}{s + 5} \quad \text{for TTS,}$$

$$W_{p2}(s) = 20 + \frac{2}{s + 0.1} \quad \text{for THR,}$$

$$W_{p3}(s) = 10 + \frac{1}{s + 0.1} \quad \text{for PTS,}$$

$$W_{p4}(s) = 20 + \frac{2}{s + 0.1} \quad \text{for JGN.} \tag{3}$$

The performance weights for the controllers at 25 and 35% load impose a larger penalty on temperature oscillations because larger temperature variations are observed at lower load levels. This quality of dynamic performance is traded off for better damage mitigation and stability. The performance weights for the controllers at 35 and 25% load are made identical as follows:

$$W_{p1}(s) = 30 + \frac{150}{s+5} \quad \text{for TTS,}$$

$$W_{p2}(s) = 30 + \frac{3}{s+0.1} \quad \text{for THR,}$$

$$W_{p3}(s) = 10 + \frac{1}{s+0.1} \quad \text{for PTS,}$$

$$W_{p4}(s) = 20 + \frac{2}{s+0.1} \quad \text{for JGN.} \tag{4}$$

The induced L_2 synthesis is performed through D–K iteration (Balas, Doyle, Glover, Packard & Smith, 1995; Zhou, Doyle & Glover, 1996). Initially, the controller at 60% had 71 states and each of the two controllers at 35 and 25% load had 79 states. Since many of the controller states were only lightly controllable, it was possible to perform Hankel model order reduction so that the order of each controller is reduced to 26 states at the final stage of design. There is no noticeable increase in the structured singular value (μ) for performance robustness that still remains below 0.8 after model order reduction.

The induced-L_2 method for multivariable robust controller design introduces a state-space structure that may limit the application of gain-scheduling because of the need to interpolate between different controllers for smooth scheduling. Parametric controllers (Nichols et al., 1993) and other smooth scheduling (pole-zero interpolation) techniques have been tested only for low-order systems. The wide range of the high-order nonlinear plant in the present design implies that the controllers may not be structurally similar in terms of the proximity of the poles and zeros. This makes it difficult to parametrize controllers. As explained earlier, the plant performance gains at different operating points are weighted differently, leading to dissimilar, high order linear controllers (e.g., 26 states after order reduction). Therefore, gain scheduling based on switched scheduling has been adopted that involves binary bi-directional switching from one controller to another with no intermediate stage. Successful implementation of the switching scheduling requires a bumpless, antiwindup transfer (Graebe & Ahlen, 1996) between controllers. Given that the controller is observable (because it is minimally realized), an observer-based policy (Graebe & Ahlen, 1996) is used for controller switching.

2.3. Fuzzy controller design

Since the role of the supervisory controller is, in part, to emulate some of the decision-making capabilities of a human supervisor, it must be embedded with the knowledge and intuitions of human operators. For this purpose, a knowledge-based system in the setting of approximate reasoning is a viable option. Yen, Langari and Zadeh (1995) have demonstrated, through various industrial applications, the ability and versatility of fuzzy logic to emulate human supervisors for decision and control. In this application, the fuzzy control algorithm serves to achieve three interrelated goals:

- *Damage rate reduction in the critical components while satisfying the plant performance requirements*: Since slow dynamics of the tracking signal (i.e., the load-following rate) may lead to loss in dynamic performance, the fuzzy control law is designed to make a trade-off between plant performance and structural damage during these transients, while taking into consideration the required plant load.
- *Robust stability of the gain-scheduled control system*: Slow variations in the scheduling variable (i.e., the plant load) facilitates stability during gain scheduling. The fuzzy controller limits the plant load variations to maintain stability without any significant deviations from the load demand.
- *Avoidance of large abrupt dynamic changes in plant variables during controller switching*: Large abrupt changes, even if they do not result in instability, may cause considerable structural damage to critical plant components. The fuzzy controller enhances smooth switching to avoid these large abrupt changes.

Holmes and Ray (1998) have proposed the basic configuration of a damage-mitigating fuzzy controller. It consists of: a fuzzifier that takes crisp inputs, an inference mechanism with a rule base and a defuzzifier that converts the fuzzy outputs in the crisp form. The nonfuzzy input to the fuzzy control system is the sensor data vector $y(t)$ that is readily available. Based on the fuzzy inputs, a course of action is adopted, via an if–then rule base that partially captures the expertise of human operators. The nonfuzzy output of the fuzzy system is the load ramp rate and the actual load (i.e., the generated power) is the gain scheduling variable. This choice provides a convenient means for achieving first goal of damage reduction. The remaining two goals can also be achieved through fuzzy logic by judicious choice of the membership functions. For example, if the goal is to achieve a smooth load increase from 30 to 60% at an average rate of 10% full load per minute, the fuzzy controller may decrease the ramp rate below 10% at certain points to maintain stability or reduce damage. On the other hand, if the sensor-based information indicates a low damage rate and stable operation, the load ramp rate can be safely increased.

The inputs to the fuzzy controller have to be measurable quantities that are available as sensor outputs. Keeping the goals of the fuzzy system in mind, the critical plant states and outputs that affect stability and structural damage need to be identified as inputs. We have discussed the effects of throttle steam temperature (TTS) and hot reheat temperature (THR) in terms of damage and their ability to reflect overall plant stability. In contrast, stability is not very sensitive to the other two plant outputs, Throttle steam pressure (PTS) and generated power (JGN). Therefore, two temperature outputs, TTS and THR, are used to derive the fuzzy controller. Both absolute temperature error and rate of temperature variation are critical to plant stability and structural damage. Thus the four fuzzy inputs are the two output temperature errors and their respective rates of variations. In this respect the fuzzy controller is analogous to a classical Proportional-derivative (PD) controller.

Similarly, the outputs of the supervisory controller must be quantities that a human operator should be able to manipulate to achieve the mission goals. The patterns and behavior of the outputs that lead to appreciable damage and instability need to be identified, observed, and incorporated into the membership functions and rule bases. The output of the fuzzy controller is the magnitude of the load ramp rate, which is the derivative of the reference signal, y^{ref} (4). During transient operations, such as ramp-up or ramp-down, the two temperatures TTS and THR are major indicators of the damage rates. In order to obtain a better control of the damage-causing variables, slowing down of the process dynamics is the most natural action of the supervisory controller. This implies a reduction in the load ramp rate. On the other hand, a good temperature performance can leave sufficient margins to increase the ramp rate, which a supervisor might choose to do. This justifies the choice of absolute value of the ramp rate as the fuzzy controller output. A unique feature of the output membership functions that are expressed in terms of the rate of change of load demand (i.e., the required load ramp rate) is their flexible nature. The membership functions are shown in Figs. 2–4.

For the two temperature errors, the same universe of discourse and membership functions are used because the process variables, TTS and THR are functionally similar. The same argument holds for the rates of change of these two temperatures. A third membership function is required for the output. Unlike the other two membership functions of temperature rate and temperature error in Figs. 2 and 3, the membership function of load ramp rate in Fig. 4 is not uniformly spaced. The spacings in Fig. 4 are obtained by trial and error over extensive simulation runs, similar to what a human operator would like to do to obtain an understanding of the physical process.

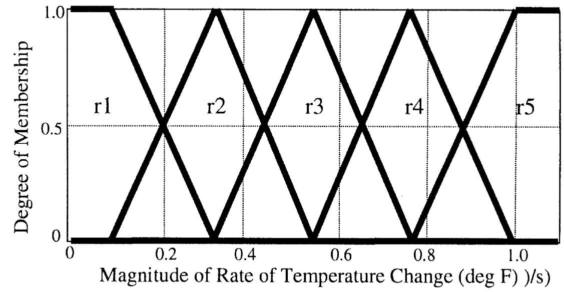

Fig. 2. Membership functions for temperature rate of change.

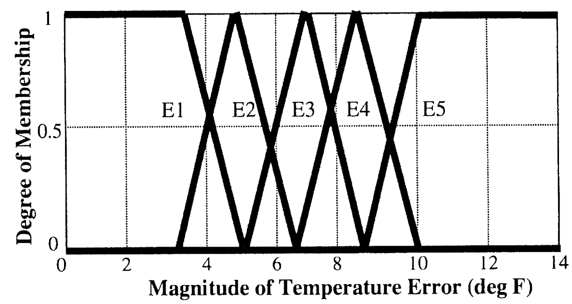

Fig. 3. Membership functions for temperature error.

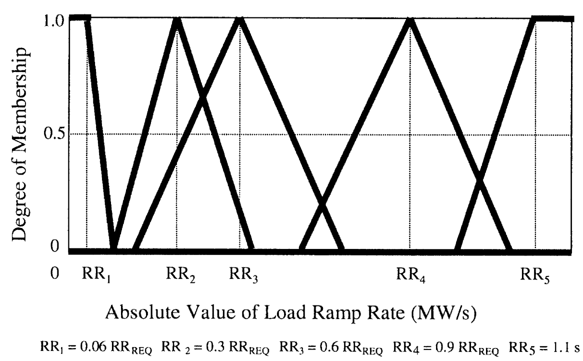

Fig. 4. Membership function for load ramp rate.

The triangular shape (i.e., piecewise linearity) of each membership function is chosen for mathematical simplicity and produces sufficiently good results, as will be seen in the next section. Each membership function set has cardinality of five. An interpretation of these membership functions from the perspectives of the supervisory controller is as follows:

- $r_1 =$ very low rate of change of temperature; $r_2 =$ low rate of change of temperature; $r_3 =$ moderate rate of change of temperature; $r_4 =$ high rate of change of temperature; $r_5 =$ very high of change of temperature.

Similar labels can be assigned to temperature error and load ramp rate.

The output membership functions are themselves a function of the required load ramp rate that is derived

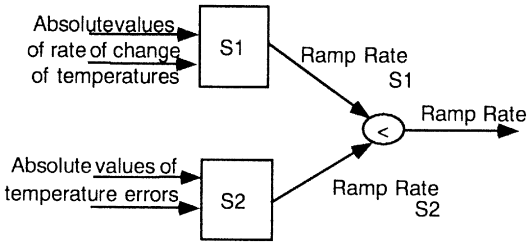

Fig. 5. Parallel processing of the fuzzy control algorithm.

from the operation strategy, which in turn is obtained from the rate of change of load, i.e., required ramp rate denoted by RR_{REQ}. The actual values of the mean of each of the five output membership functions (see Fig. 4) are:

$$RR_1 = 0.06\ RR_{REQ}, RR_2 = 0.3\ RR_{REQ}, RR_3 = 0.6\ RR_{REQ},$$

$$RR_4 = 0.9\ RR_{REQ}, RR_5 = 1.1\ MW/s.$$

These values are arrived at through trial and error and are based on human experience. They are specific to the power plant under consideration and can be easily modified on-line to achieve a different level of performance-damage trade off. For this specific plant, the highest value of ramp rate is 1.1 MW/s that can be achieved only during near 'perfect' stability and very low damage rates.

The membership functions are now combined into a set of fuzzy rules constituting a four input–single output fuzzy control system with each input having cardinality of five. This implies that there can be 5^4 (= 625) combinations of inputs and an if–then rule is required for each combination. To simplify this situation, the fuzzy control system is partitioned into two parallel processing systems S1 and S2 as shown in Fig. 5. The inputs to S1 are temperature rates and the output is the load ramp rate, while the inputs to S2 are the temperature errors and output is also the load ramp rate. The junction ' < ' in Fig. 5 represents an operation which picks the minimum of the two outputs, i.e., the slower ramp rate. The advantage of this simplification is that, instead of 625 rules, two sets of 25 if–then rules are now needed as listed in Tables 2 and 3.. For example, a rule *If* r_1^{TTS} *and* r_1^{THR}, *then RR5* represents: *If the rate of change of Throttle Steam Temperature is very low and the rate of change of Hot Reheat Temperature is very low, then ramp rate should be made very high.*

The membership functions fuzzify the nonfuzzy inputs. In the inference mechanism, the parameter λ_{ij} is used to express the applicability of each of the 25 rules to the present situation. It takes a value in the interval [0,1] representing a measure of the amount the inputs satisfy the *if* part of the respective rule. The subscripts i and j represent the row and column of the rule matrices. For example, $\lambda_{ij} = \min\{r_i^{TTS}, r_j^{THR}\}$ referring to Table 2 where the rows (i.e., subscript i) and columns (i.e., subscript j) indicate the membership values of functions involving TTS and THR, respectively. The defuzzifier calculates a unique output in the form of ramp rate. The output is calculated as a weighted average of the outcome of each rule, RR_k, $k = 1,2,3,4,5$, with the respective λ_{ij}'s as the weights. The outcome of each rule is represented as rr_{ij} where a unique value of rr_{ij} is determined as the outcome of each *if–then* rule. The three middle membership functions, RR_2, RR_3, and RR_4, in Fig. 4 are symmetric. For these three functions, each outcome rr_{ij} is concentrated on its respective geometric mean (i.e., center of gravity). For the two remaining membership functions, RR_1 and RR_5, the outcome rr_{ij} is, respectively, equal to the largest and smallest ramp rates with membership value of one. The defuzzified ramp rate is given by

$$\text{ramp rate} = \sum_{i,j=1,\ldots,5} \lambda_{ij} rr_{ij} \Big/ \sum_{i,j=1,\ldots,5} \lambda_{ij} \tag{5}$$

which is the weighted average of the geometric means of the output membership functions.

Table 2
If–then rules for temperature rate of change (fuzzy controller S1)

	r_1^{THR}	r_2^{THR}	r_3^{THR}	r_4^{THR}	r_5^{THR}
r_1^{TTS}	RR_5	RR_4	RR_3	RR_2	RR_1
r_2^{TTS}	RR_4	RR_4	RR_3	RR_2	RR_1
r_3^{TTS}	RR_3	RR_3	RR_3	RR_2	RR_1
r_4^{TTS}	RR_2	RR_2	RR_2	RR_2	RR_1
r_5^{TTS}	RR_1	RR_1	RR_1	RR_1	RR_1

Table 3
If–then rules for temperature error (fuzzy controller S2)

	E_1^{THR}	E_2^{THR}	E_3^{THR}	E_4^{THR}	E_5^{THR}
E_1^{TTS}	RR_5	RR_4	RR_3	RR_2	RR_1
E_2^{TTS}	RR_4	RR_4	RR_3	RR_2	RR_1
E_3^{TTS}	RR_3	RR_3	RR_3	RR_2	RR_1
E_4^{TTS}	RR_2	RR_2	RR_2	RR_2	RR_1
E_5^{TTS}	RR_1	RR_1	RR_1	RR_1	RR_1

2.4. Control system implementation

The implementation strategy of the supervisory control system, shown in Fig. 6, has three main functional modules where the discrete-time and continuous-time signals are denoted by 'k' and 't', respectively, in parenthesis. The supervisory controller module consists of the gain scheduler and the fuzzy controller. The gain scheduling of controllers is carried out based on the measured plant outputs $y(k)$, specifically the fourth element of $y(k)$, which is the generated load JGN in MW. Given a power plant operating strategy, the fuzzy-logic-based control module in the supervisory controller serves the role of

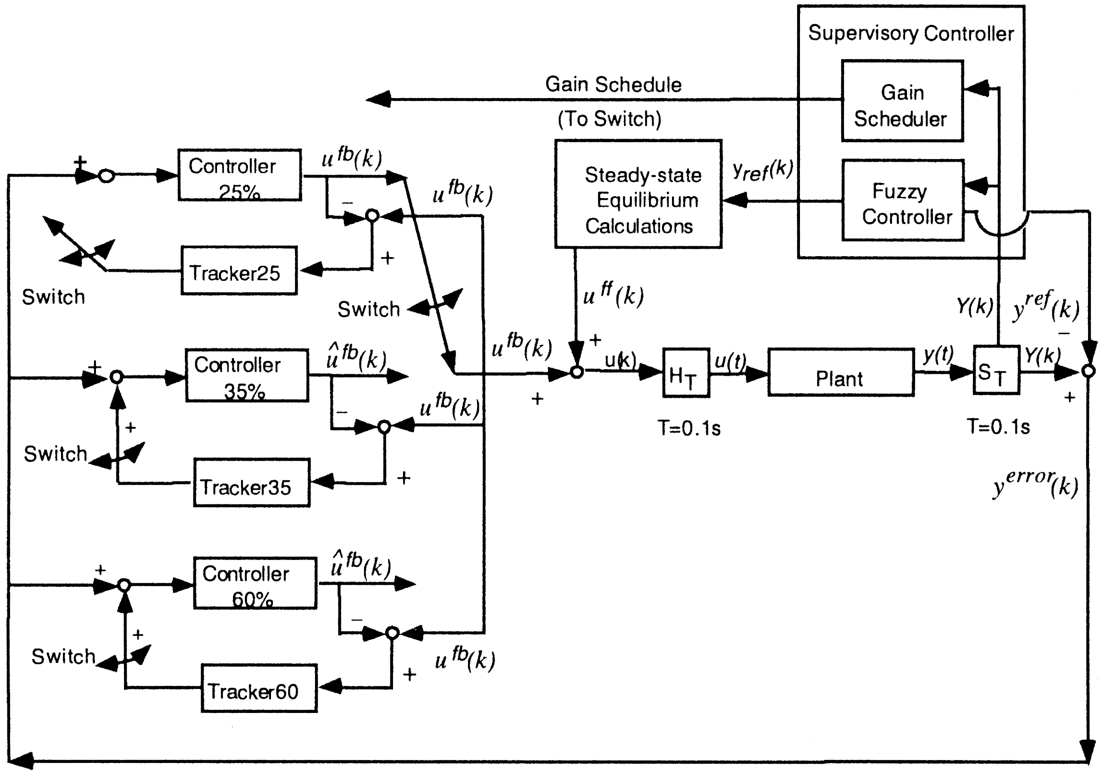

Fig. 6. Implementation of supervisory control system.

generating $y^{\mathrm{ref}}(k)$. The feedforward signal is generated via equilibrium steady-state calculations. The robust feedback module is realized by three linear controllers whose ranges of operation are as follows:

- controller synthesized at 25% plant load: used for range [25%, 32%] plant load;
- controller synthesized at 35% plant load: used for range (32%, 50%] plant load;
- controller synthesized at 60% plant load: used for range (50%, 100%] plant load.

All three controllers are synthesized closer to the lower end of their operating range. The rationale is that the extent of nonlinearity is much more severe as the load is diminished.

The sequence $u^{\mathrm{ff}}(k)$ of the feedforward signal is updated every 1 s by the fuzzy controller, based on $y^{\mathrm{ref}}(k)$, and is stored in the control computer a priori. The feedback control law $u^{\mathrm{fb}}(k)$ is generated on a 0.1 s sampling time. At each sampling instant, the feedforward and feedback signals are added together and are converted into a continuous-time signal using the zero-order hold (ZOH) logic. Since the feedforward sequence is based on a 1 s sampling time while the feedback control is based on a 0.1 s sampling time, each element in the feedforward sequence is applied for 10 consecutive sampling intervals. The error signal, $y^{\mathrm{error}}(k)$ is obtained by subtracting the reference signal $y^{\mathrm{ref}}(k)$ from the plant output $y(k)$.

The first three elements, namely reference signals for TTS, THR and PTS, of $y^{\mathrm{ref}}(k)$ are functions of the fourth element (i.e., the reference signal for JGN). Once the vector $\{y^{\mathrm{ref}}(k)\}$ is determined, it can be used to generate feedforward input for the next sample. At any instant, only one linear controller provides the feedback signal. While a single specific controller is on-line, the trackers for the remaining two controllers, which are off-line, are functioning to ensure that the controllers are ready to switch smoothly under a sudden change in the plant load demand. As soon as the active controller goes off-line, its tracker is switched on. While the main role of the supervisory controller is life extension without any significant loss of performance, it ensures stability and augments the operating range of the power plant. It is shown in the simulation section, that at times when the feedback controllers fail, the supervisory controller can maintain robust stability.

3. Results and discussion of simulation experiments

Simulation experiments are performed to demonstrate performance, robustness and damage mitigating capabilities of the wide-range control system. This is accomplished by comparison of the plant dynamic performance under the following three feedback control system configurations:

Case 1: *Single controller*: A single induced L_2 robust controller designed to operate over the entire range of plant operation (i.e., 25–100%);

Case 2: *Gain scheduled without fuzzy logic* (denoted as 'gain sch.'): A combination of three gain-scheduled controllers without fuzzy logic to operate over the entire range of plant operation;

Case 3: *Wide range control system/gain scheduled with fuzzy logic* (denoted as 'gain sch. with fuzzy'): A combination of three gain-scheduled controllers along with a fuzzy logic to operate over the entire range of plant operation.

Each of these feedback control configurations is used in conjunction with the same feedforward policy. These three cases are compared based on output performance and structural damage. The plant performance requires generated plant load (JGN) to follow a predetermined trajectory. The other three outputs, namely, throttle steam temperature (TTS), hot reheat temperature (THR) and throttle steam pressure (PTS) follow trajectories based on the current plant load and are maintained within respective bounds. During these operations, damage accumulation in each of the main steam header, hot reheat header and superheater tubes is calculated using the damage models reported in the earlier publication (Kallappa et al., 1997). Simulation experiments are also performed to test robustness of the control system under plant perturbations.

3.1. Simulation set up

For both nominal and perturbed plant conditions, the closed-loop control system is evaluated by simulation of two operation scenarios: a power ramp up from 25 to 100% The recommended ramp rate is 10% (of full load) per minute for both operations. This makes RR_{REQ} to be 0.875 MW/s. The desired operating conditions for the TTS, THR and PTS at a given plant load (JGN) become algebraic functions of the JGN and are determined as the steady state values of these outputs at the given plant load. At loads above 40% of the full power level, these set point values are maintained unchanged. However, at loads below the 40% power level, the set points need to be decreased, especially the pressure PTS. The steam pressure difference across the feedwater pump turbine is insufficient to generate adequate power to drive the feedwater pump at low loads. Since it becomes difficult to maintain pressure at 2415 psi (16.65 MPa) without actuator saturation, the reference signal for PTS is lowered for operations below the 40% load level. The operating temperatures are also lowered slightly to avoid actuator saturation.. The operating conditions for each load are as follows:

- 25% load - [TTS, THR, PTS] = [935°F (501.7°C), 990°F (532.2°C), 2050 psi (14.13 MPa)];
- 30% load - [TTS, THR, PTS] = [948°F (508.9°C), 998°F (536.7°C), 2285 psi(15.75 MPa)];
- 40–100% load - [TTS, THR, PTS] = [950°F (510.0°C), 1000°F (537.8°C), 2415 psi (16.65 MPa)].

A brief description of the geometry, materials and type of damage in the three components are given below:

Main steam header: It is made of $2\frac{1}{4}$% Chromium and 1% molybednum ferritic steel. It has an inner diameter of 4.5 in (114.3 mm) and an outer diameter of 7.2 in. (182.9 mm). Damage in main steam header results from fatigue cracking and, thickness reduction due to creep. Normalized creep is obtained as the reduction in header thickness per unit original thickness and is designated 'Creep Thinning'. Maximum fatigue crack growth occurs on the outer surface of headers in the radial direction.

Hot reheat header: It is made of $2\frac{1}{4}$% chromium and 1% molybednum ferritic steel. It has an inner diameter of 6.5 in (152.4 mm) and an outer diameter of 7.0 in (177.8 mm). Damage in the hot reheat header is predominantly due to creep and is represented as 'Creep Thinning' in a fashion identical to the creep damage in the main steam header.

Superheater: Each superheater tube is made of $2\frac{1}{4}$% chromium and 1% molybednum ferritic steel. It has an inner diameter of 1.0 in (25.4 mm) and an outer diameter of 1.75 in (44.45 mm). Structural damage in superheater tubes occurs mainly due to creep and is also represented as 'Creep Thinning'.

The steam temperatures and pressure, TTS, THR and PTS, determine stress conditions in the main steam and hot reheat steam headers as well as in the steam generator and reheater tubes and in the high-pressure and intermediate-pressure turbines. The next two sections present simulation results for nominal and perturbed plant conditions. The plots in the figures are marked with appropriate labels (e.g., 'single controller', 'gain sch.', and 'gain sch. with fuzzy') to indicate different controller configurations under both ramp-up and ramp-down operations. The term 'Ref. Traj.' in the figures denotes 'Reference Trajectory'. Results from power ramp up operation are reported for both nominal and perturbed plant, because each of these simulations highlights a different aspect of the system. Since ramp-down operations for both nominal and perturbed plant yield similar results, only the simulation results for the perturbed plant are reported here.

3.2. Simulation under nominal conditions

Three different configurations of feedback control are used as mentioned earlier. The single robust controller, adopted for simulation experiments, yields the best performance out of many single controllers that were designed and tested. This controller is designed based on the plant model linearized at 40% full load. Fig. 7 shows

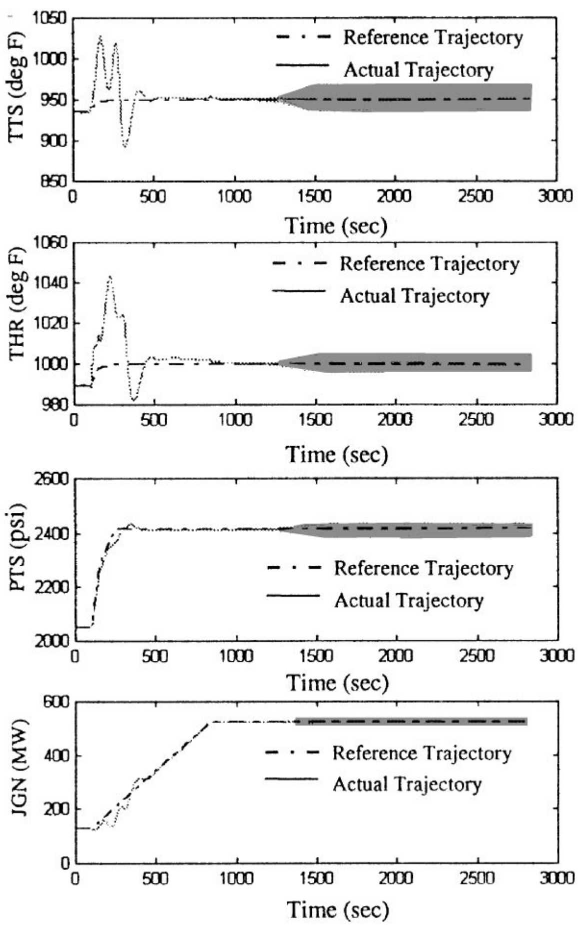

Fig. 7. Ramp-up performance of a single controller in the nominal plant model.

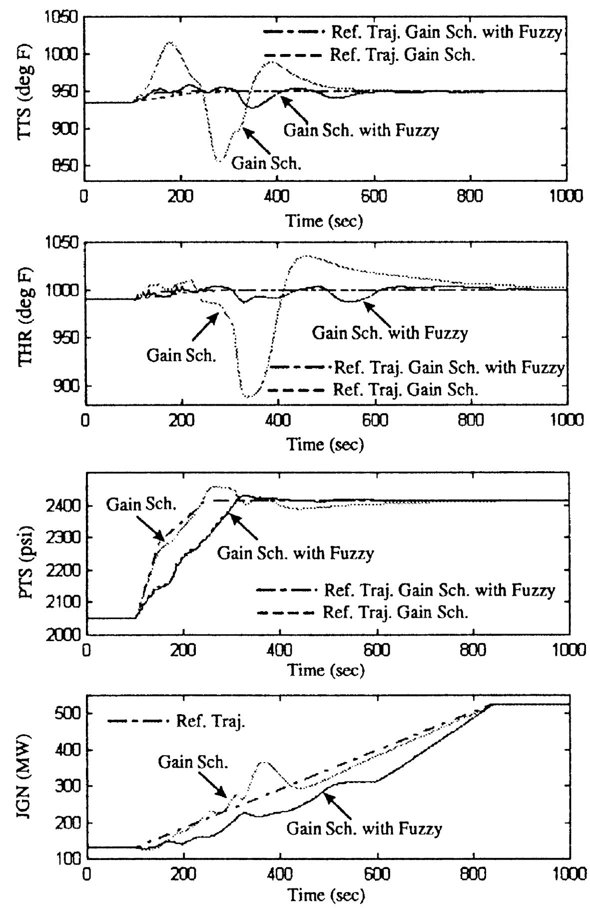

Fig. 8. Ramp-up performance of gain-scheduled controllers in the nominal plant model.

the performance of this controller for ramp-up operations. The plots show that the respective initial steady-state load is held constant for the first 100 s to demonstrate absence of any initial (non-steady-state) transients. Similarly, the final steady states are held for an extended period of time to exhibit stability. Throttle steam and hot reheat steam temperatures, TTS and THR, in Fig. 7 abruptly increase at the onset of power ramp-up. Rapid temperature changes of this nature may cause structural damage in the steam headers as well as in the steam turbines. The final steady state responses are also extremely oscillatory. This is undesirable for the perspectives of both performance and structural damage. The single controller is also found to be unstable for injected plant perturbations. It is reiterated that this single controller has yielded the best performance out of a large group of single robust controllers that were designed.

Fig. 8 compares the outputs of the 'gain sch.' (i.e., without fuzzy logic) and 'gain sch. with fuzzy' controllers under ramp-up. Gain scheduling shows a marked improvement over the 'single controller' system in terms of steady-state behavior although the transient response is still poor. In contrast, the 'gain sch. with fuzzy' controller shows excellent behavior of the steam temperature and pressure transients. Unlike the other two controllers, 'gain sch. with fuzzy' significantly diminishes the risk of potential damage to the steam turbines by reducing thermal stresses arising from large temperature oscillations. The 'gain sch. with fuzzy' system in Fig. 8 takes 738 s for load ramp-up from 25 to 100% (i.e., an average ramp rate of 6.1% of full load per minute). This fuzzy controller reduces the load ramp rate to ensure stability and low damage rate; it also increases the load ramp rate when it is safe to do so. A major goal of the 'gain sch. with fuzzy' control system is to ensure that the generated power JGN closely follows the reference trajectory where enforcement of a very small tracking error may induce large oscillations in steam temperature and pressure resulting in increased damage. There is thus a trade-off involved. The load-following performance can be improved by changing the frequency-dependent performance weights W_p in the robust feedback controller synthesis as well as by updating the fuzzy membership functions (e.g., allowing larger ramp rates in the membership functions of the plant outputs). Each change involves a trade-off and is the designer's decision. In essence, the fuzzy controller

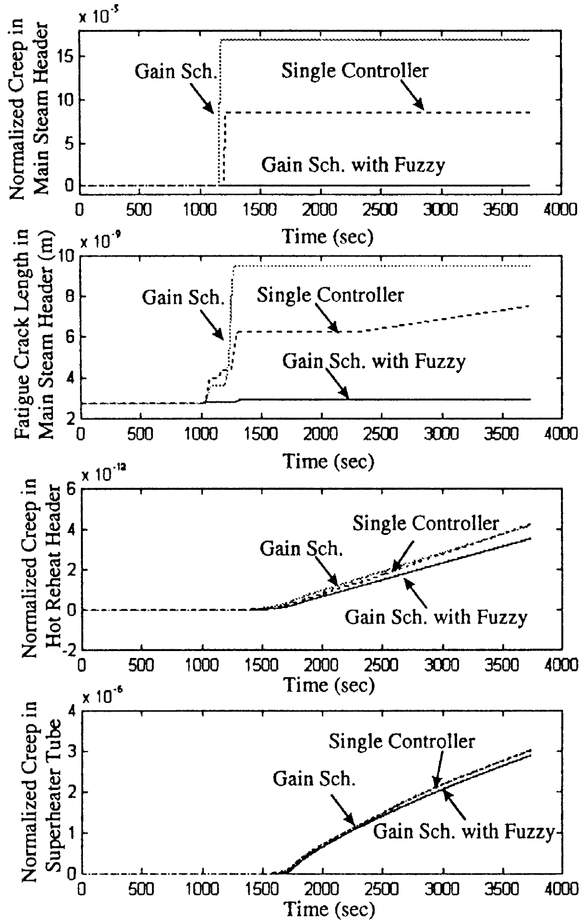

Fig. 9. Damage during ramp-up operation in the nominal plant model.

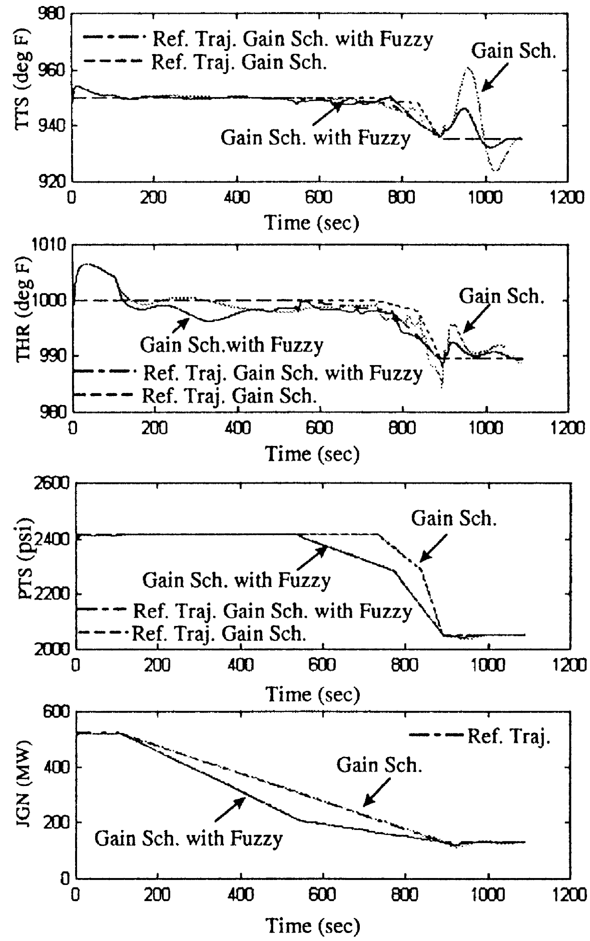

Fig. 10. Ramp down performance of the perturbed plant model.

can be designed to improve the transient response of JGN at the expense of structural damage or vice versa.

Fig. 9 compares the structural damage under a ramp-up operation that is preceded by 1000 s of steady-state and followed by 2000 s of transients. This ensures that any delayed dynamics in damage will show up during steady state operation. For each of the critical components, the 'gain sch. with fuzzy' controller yields better damage mitigation. Maximum damage reduction takes place in the main steam header because it is a thick pipe and is more prone to thermal stresses arising from larger temperature gradients across the wall. The hot reheat header, on the other hand, is a thinner pipe and its damage is mainly due to the temperature; temperature variations have much less detrimental effects. A similar logic applies to the superheater tubes that are not as thick as the main steam header. The main cause of structural damage in superheater tubes is the radiant heat flux from the fireball in the furnace. The fireball size is controlled by the air–fuel valve. Under nominal plant operations, the feedforward control input to this valve is carefully designed to avoid any sudden change in fireball size and the feedback signal is responsible for fine-tuning only. Therefore, the life extending qualities of the feedback system for the superheater tubes are not as evident in the nominal plant, compared to those in the perturbed plant. To summarize, it is concluded that 'gain sch. with fuzzy' is the best amongst the three controllers for performance and damage mitigation.

3.3. Perturbed plant simulation

Simulation experiments have also been conducted on the plant model with injected perturbations to examine robustness of the control system. The following perturbations are introduced:

- 3% decrease in the efficiencies of all turbines and pumps due to structural degradation of rotating components;
- 3% decrease in the heat transfer coefficients in the steam generator and reheater tubes due to scale formation on the inside surface;

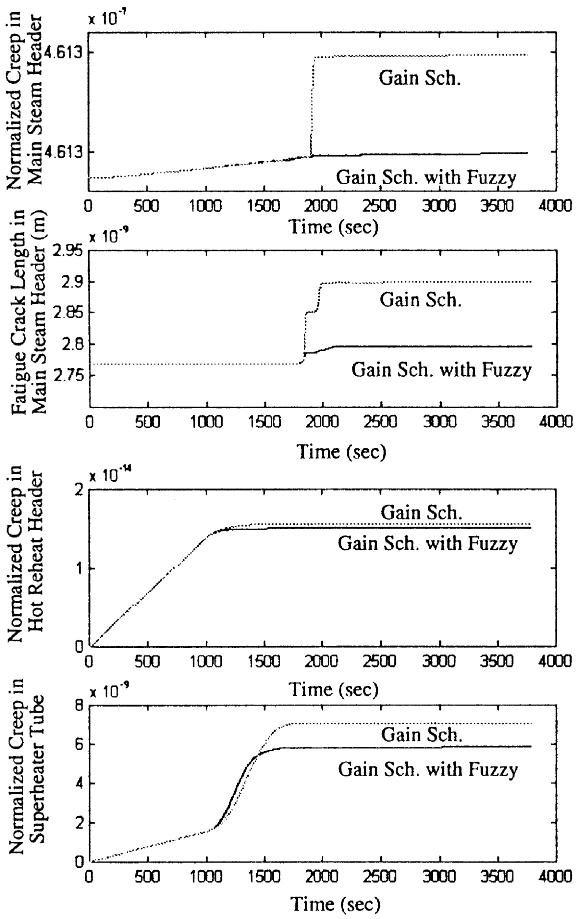

Fig. 11. Damage during ramp-down in the perturbed plant model.

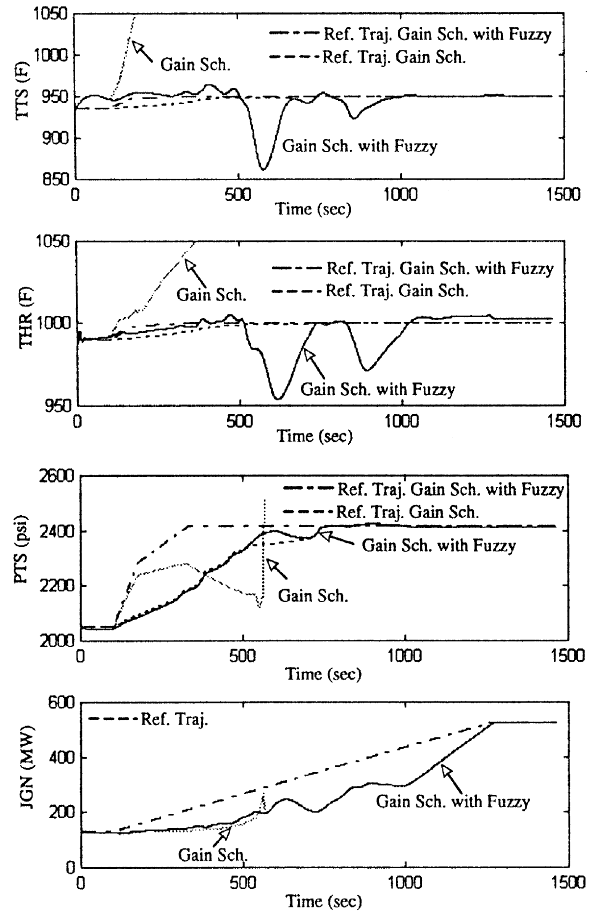

Fig. 12. Ramp up performance of the perturbed plant model.

- 25% increase in the time constants of the governor, feedpump turbine and fuel/air valves due to possible actuator degradation.

The 'single controller' is unstable under perturbed conditions for both ramp-up and ramp-down and the results are not presented here. A comparison of the 'gain sch.' and 'gain sch. with fuzzy' controllers in Fig. 10 shows improvements in the throttle steam and hot reheat steam temperatures, TTS and THR. The 'gain sch. with fuzzy' controller yields superior performance in terms of overshoot and oscillations, especially in the later part of transients. The response of the throttle steam pressure, PTS, is good for both controllers. The generated power, JGN, exhibits the trade-offs. Without the fuzzy controller, the transient response of JGN is modestly superior at the expense of other variables and specifically structural damage in the main steam header as seen in Fig. 11. This also demonstrates the basic features of the fuzzy controller. When the steam temperatures are well within specified limits, the 'gain sch. with fuzzy' controller increases the ramp and when the temperatures begin to oscillate, it lowers the ramp rate as seen in the bottom plate of Fig. 10. For both ramp-up and ramp-down operations under 'gain sch. with fuzzy' control, reduction in damage in one component does not result in increased damage in another component. There are no trade-offs involved at this level. All trade offs are made among the plant outputs where the power ramp-up or ramp-down rates under load-following operations may have to be slightly sacrificed to prevent large oscillations in steam temperature and pressure. It is concluded that good control of steam temperature and pressure transients leads to mitigation of structural damage in plant components.

Fig. 12 shows the ramp-up operation for the perturbed plant. The 'gain sch. with fuzzy' controller performs reasonably well and the control system becomes unstable without the fuzzy controller. As the generated power JGN starts to move away from its reference trajectory, the fuzzy controller slows down the load ramp rate and thereby the rate of change of the plant load is reduced and stability is maintained. This is in accordance with the statement in Section 2 that slow variation of the gain scheduling variable, in this case the plant load, ensures stability. This observation demonstrates the effectiveness of fuzzy logic in keeping the control system robust.

4. Summary and conclusions

This paper presents a methodology for synthesis of life extending control systems for wide range operations of fossil-fuel steam power plants. The goal is to achieve damage mitigation in critical plant components and to enhance dynamic performance and robustness of the power plant control system. Since the fuzzy controller makes the decision of changing the load reference signal based on damage predictions, it can react to unexpected changes in real time, which cannot be predicted a priori. A distinct feature of this approach is that the knowledge of plant dynamics and mechanics of the structural materials are synergistically applied to formulate a controller design methodology which can be readily used by practicing engineers with the aid of commercially available software.

A combination of three gain-scheduled controllers is used as the linear feedback system in the lower tier of the hierarchical control system. Since power plant dynamics are more nonlinear at lower loads (because of reduced water/steam flow rate), the controllers are synthesized at 25, 35 and 60% of full load. The (frequency-dependent) performance weighting functions for these controllers are selected after a careful study of the plant and damage dynamics to simultaneously achieve robust performance and structural durability.

A supervisory control system in the upper tier is created for: (i) implementation of gain scheduling; (ii) enhancement of life extension capabilities; and (iii) increased stability robustness. The supervisor consists of a fuzzy-rule-based controller that captures the expert knowledge of plant dynamic stability and structural damage in the critical components. Implementation of these rules leads to dynamically smooth switching between controllers under gain scheduling. It enhances robust stability of plant operations and simultaneously reduces structural damage. The fuzzy controller design does not require any direct use of the nonlinear plant model and damage models. The fuzzy supervisor is designed based on a given trade-off between tracking error under load-following and damage rate. Results of simulation experiments show that the ramp rate is reduced from 10% to just over 6% to reduce the damage rate. The level of trade off can be altered by using a combination of the following strategies:

- *Changing the mean values of the ramp rates*: The mean values of the ramp rates are increased for better performance and they are reduced for improved stability and life extension. This modification can be executed on-line.
- *Changing the input membership functions*: The permissible errors and rates of change are reduced to maintain the damage rates low and they are increased for better performance. This is a design modification that can only be executed off-line.

Based on the results of simulation experiments, it is apparent that reduction of damage in one component does not lead to increase in damage in other components. It also establishes the overall superiority of gain scheduling with fuzzy control, especially for power ramp-up operations. This concept of wide-range life extending control is of significant engineering importance.

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