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A Review of Structure & Performance of Thermal Power Plant Controllers

Roopa Sampath*, Sukhdeep. S. Dhami** and Suresh Srivastava***

**Ph. D. Scholar, Department of Mechanical Engineering, Panjab University Chandigarh, INDIA*
***Professor, Department of Mechanical Engineering, NITTTR, Sector 26, Chandigarh, INDIA*
****Director Technology, Director- General, Aeronautics, DRDO, Bangalore, INDIA*

(Corresponding author: Roopa Sampath)
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ABSTRACT: Power systems are complex mechanisms which are highly nonlinear in behavior. Various approaches are used for modeling and control of these non-linear systems. This paper presents a review of various types of controllers & techniques used for control of various parameters affecting the performance of the power plant. The survey has been presented in terms of different kinds of controllers developed with various objectives of control & techniques deployed for developing the control systems. The advantages and the disadvantages of the various modeling methods and techniques are also listed.

Key words: Thermal Power Plant Controllers, Conventional controllers and Nonconventional controllers.

I. INTRODUCTION

Research has been done for control of different parameters in various models of boiler turbine units. A literature survey has been made on the controllers designed to control various parameters for better performance of the thermal power plant. The most general control parameters at the inlet are pressure, temperature, mass flow rate of steam or fuel used. The controlled output has been measured in terms of speed, torque, efficiency, and power. The techniques for effecting control of thermal plant are fuzzy logic, neural networking, model predictive methods and optimization approaches like Genetic algorithm, Partial Swarm Optimization, Bacterial Partial Swarm Optimization etc.

II. CONTROLLERS USED IN THERMAL POWER PLANT

Broad categorizations for classifying the various controllers developed for thermal power plant are Conventional controllers and Nonconventional controllers.

Conventional controllers. Conventional controllers are widely used in industries due to low cost and ease of implementation. They could be proportional, integral, derivative or a combination of proportional & integral, combination of proportional and derivative or a combination of all the three. The performance of these conventional controllers has been enhanced by tuning using various methods such as Zeigler - Nichol's and Simplex method. Conventional controllers have many advantages such as ease of implementation, simple constructions and low cost of construction and ease of tuning. The use of various conventional controllers for control of various parameters to get optimal plant performance as reported in the literature is presented in this section.

Mircea *et al.* [1] presented the mathematical model of a steam turbine power unit in terms of turbine torque relation with the steam flow rate to the turbine. The equation was developed using the continuity equation and thermodynamic principles. A proportional controller was developed for the plant model to obtain an optimal speed. This in turn regulated the power generated from the plant. The value of the tuning parameter of the proportional algorithm was determined for a stable response. Based on the developed characteristic equation it was found that for any value of the tuning parameter greater than zero, a stable response will be obtained. For values $0<K<0.67$, a damped stable response was obtained. The behavior of the shaft torque with the changes in the high pressure valve openings and the re-heater valve openings were observed. The P controller exhibited a stable response and showed good performance in terms of time domain in closed loop connection. Kallol *et al.* [2] developed classical controllers to control load frequency in an Isolated Single Area Power System & Two Area Reheat Thermal Power System. Single area system considered for work comprised of a governor, a turbine and a generator with a feedback regulation constant. It also included a step load change input of 1% change in demand load at 2.4 Hz/p.u MW to the generator.

Classical controllers like Integral, PI, and PID controllers were used for control. Generation rate constraints were included to compensate for the system non-linearity. The load agitation in one area affected the other area, as the two areas were interconnected. The responses of the deviation in frequencies, deviation in tie line power, with the choice of different controllers (I, PI& PID) with different gain values for better dynamic responses have been plotted. The various characteristics like the rise time, settling time, oscillations and peak overshoot were observed. Frequency deviation was also evaluated. On comparison of performance of all controllers considered, PID controllers have proved to give the best results for both frequency and tie line power. Tuning of these controllers also aided the achievement of good responses and stability with a minimum error or disturbance. However, the purpose of this controller was defeated when disturbance was large. Work towards controller design which did not get affected by disturbances was required to be undertaken.

Ertugrul *et al.* [3] developed a fuzzy gain scheduled proportional and integral controller to regulate and improve the frequency deviation in a two area electrical interconnected power system. A conventional integral (I), proportional and integral (PI) & a fuzzy logic (FL) controller were used to control the same power system for performance comparison. The settling time and the overshoots of the frequency deviation were considered for performance evaluation. The number of rules for the inference mechanism was taken as 7 so that the controller performances were improved by increasing the rule numbers to 49. The simulation results showed that the Fuzzy Gain Scheduling of the PI, (FGPI) controller developed in this study performed better than the other controllers with respect to the settling time, overshoot and absolute error integral of the frequency deviation. The author has recommended the use of FGPI for generating good quality and reliable electrical energy. It was concluded that transient response could be unstable because of abruptness in system parameters. At various operating points various linear time invariant models would be required for accurate operation.

Heon *et al.* [4] developed an integral controller to control frequency in a steam turbine power plant. Generation Rate Constraints were used to get rid of the overshoots of the conventional PI controller. This controller did not yield adequate control performance even after the consideration of singularities GRC. In order to overcome this drawback, an extended integral control was developed for the PI control of the speed governor under the presence of GRC. This control scheme was based on optimal tracking approach. This was modified with the usage of decaying factor to reduce the effect of errors in the past. It is represented by the convolution integral. The simulation results have showed that the proposed controller yielded much improved control performance than the conventional PI controller. The exploration of Artificial Intelligence based techniques for identification of the optimal parameters of the integral controller was yet to be worked.

Anil *et al.* [5] proposed a fuzzy controller to quench frequency deviation in a two area interconnected power system in different load conditions. The model has been defined as a state transfer problem and changes due to loading conditions are sensed in terms of rotor angle changes. An acceptable rotor angle change would result in an acceptable level of power quality keeping the voltage and frequency in the tolerable limits. The fuzzy controllers developed were further tuned using various tuning rules. The performances of these controllers were compared with I & PI controllers. The performances of the fuzzy controllers were shown in terms of improvised settling time & overshoots. Conventional I & PI controller could not reach the required performance criteria. Emphasis on the essential need for catering the dynamics of the power system in the model has been made.

C Vlachos *et al.* [6] developed a method for the tuning of a multi loop PI controller for a multivariate process of a boiler turbine unit using genetic algorithms (GA). Tuning of PI was done using Genetic Algorithms (GA). The flexibility and effectiveness were illustrated by the authors in three multivariable processes with different degrees of interaction. The authors concluded that in all cases, GA tuned PI controllers were optimal and the closed loop systems completely satisfied all the performance objectives. The programs were simulated in Matlab. The performance objectives were overshoot $\leq$ 20%, and settling time $\leq$ 50 min. The authors concluded that controllers tuned with GA were robust and immune to noise with a success rate of 71% - 85% compared to controllers with SQP. They showed only 2% success in noise free case. Simulation results showed all controllers tuned by GA methods met the required performance objectives. The disadvantage of the proposed method was off line tuning requirement due to the large number of closed loop tests.

Horacio *et al.* [7] implemented a multi-loop PI control in a boiler turbine system for a co-generation system using H_∞ loop shaping techniques. To practically implement this, reduction of this H_∞ controller to a multivariable PI controller was considered. Linear time variant models (LTI), a good approximation to nonlinear plant models were obtained based on the input output measurements of the utility boiler system. This H_∞ controller had the order of 18. The practical implementation of this controller required the model order reduction. PI type was investigated because of its easy anti wind up implementation. The authors finally presented the comparison of three controller's namely approximated PI controller, multi loop PI controller and H_∞ controller.

The multi loop PI controller and the approximated PI controller showed lesser stability in terms of settling time in the order of 5 minutes and the overshoot in the peaks were reduced by 20 decibels in the H_∞ controller. However the final results were needed to be tested for vigorous conditions in more accurate descriptions incorporating the nonlinearities in the true plant.

Lin *et al.* [8] developed a fuzzy PI controller to control steam pressure in a 300 MW steam boiler turbine unit. A second order neuro fuzzy model of a combustion system was used for controller development. This controller was compared with Linear Regression (LR) and Multi Layer Perception (MLP) models developed for second order linear models. Fuzzy PI showed better performance than LR & MLP controllers during load changes and time delays. Its performance was verified in Digital Control System (DCS) for point tracking and load disturbance. This process was suitable for processes whose model parameters did not change with working conditions.

Bonissore *et al.* [9] developed a fuzzy control system for the start up of the steam turbine in the stages following pre-warming. A fuzzy PID was developed for the knowledge base. The aim was to extend the turbine life and minimize the time for attaining the required turbine component temperatures. Also the constraints of limit steam flow, limit temperature gradient and minimum build up of the condensate in the shell of the turbine was simultaneously considered. The authors achieved the required control objectives by enhancing the conventional PI controllers with the fuzzy system. The parameters of interest were focused on the rotor bore and surface temperatures, rotor speed and condensate accumulation in various turbine sections. The results showed that a faster pre-warming rate had three advantages. It reduced the condensate accumulation to zero. The rotor bore stress was well below the allowable limits of 6500 psi. The rotor bore attained a temperature of 300˚F only after a long time of 12 hours. However the results proved the need of an effective operator input to the fuzzy supervisor which controlled the overall performance.

Ertugrul *et al.* [10] presented a fuzzy control to regulate and improve the frequency deviations using fuzzy gain scheduling techniques for PI controllers for a two area interconnected power system. The results from simulation showed that the gain values of the proposed controller settled faster in comparison to the other controllers. The system response of the proposed controller had approximately equal overshoots but a very short settling time. Instantaneous load changes were made for various cases and a good success was obtained. Proposed algorithm thus proved very effective and significant. Comparison of the PI controller, other fuzzy gain scheduling controllers and proposed fuzzy gain scheduling of PI (FGPI) controllers have been presented. The author proved that the proposed FGPI controller could generate the best dynamic response following a step load change. However, there was a continuous requirement of constantly optimizing the P and I constants to achieve a stable response as the disturbance varied. This was time consuming.

Sateesh *et al.* [11] worked on load frequency control in a two area interconnected power system using fuzzy controllers. The mathematical model used for controller design constituted a turbine, generator, governor and load. The control objective was to regulate the frequency in the two areas and simultaneously regulate the tie line power as per the inter area power contracts. The PI controller in the forward path was introduced to change the controller output corresponding to the proportional plus integral of the error signal. This increased the system order type and reduced the steady state error tremendously for the same number of inputs. In the fuzzy controller, the inputs to the systems are the error and change in error of the feedback loop. The responses of the proposed controller was very fast, having a less undershoot and a very negligible overshoot with a very small state transfer time to reach the final state. The author suggested other different techniques like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Artificial Neural Network (ANN) method for reducing frequency deviation.

Horacio *et al.* [12] developed a linear controller for a non linear boiler turbine unit for a chosen operating range. A linear controller was designed via loop shaping H_∞ approach. Anti- wind up compensation was applied on the single linear controller and the controller proved to work very well in the operating range. The authors presented the results after simulation for three different cases. The performance of the controllers was assessed in the various ranges. The gap between the two controllers at final operating range and nominal range was 0.154. As the operating range was increased further; the gap increased to 0.727. AWBT techniques were applied to the above controller and the gap was reassessed. The gap reduced to 0.335 between the two operating points. A tradeoff between the ease to use and cost to implement the nonlinear controllers in plant and tune them exists. A more sophisticated model of boiler turbine unit could yield a better controller design.

M.H Toodeshki *et al.* [13] developed a Model Reference Adaptive Controller (MRAC) for a non linear boiler turbine system for a class of non linear Multi Input Multi Output Systems (MIMO). These systems were chosen such that their state equations matched the boiler turbine state equations. Lyapunov functions were used to achieve closed loop stability, output tracking with zero state error and perfect performance against changing parameters. The effectiveness of the presented method was proved by introducing six uncertain parameters on a proposed boiler turbine model. A PID controller was developed for performance comparison.

The coefficient of this PID controller was tuned using the stable inversion method and H $_\infty$ robust method. Simulation showed the closed loop system was unstable when six parametric uncertainties were introduced. The controller could be used only for a specific range and needed to be modified to cater for rejection of the effect of the parametric, nonparametric uncertainty and disturbances. With the proposed MRAC method, closed loop system was stable and desired performance was satisfied. It was concluded that MRAC effectively rejected the effect of parametric uncertainties, simultaneously removing the effect of disturbance and non parametric uncertainties. However this was not applicable to non linear boiler turbine with time delays and required state output feedback.

H. Nademi *et al.* [14] designed a multivariable PID controller for the governing system of the steam turbine power generators in a combined cycle power plant in Damavand. This plant included the governor, exciter, turbine and generator as per IEEE standards used for load frequency control studies. A multivariable PID controller was designed for the governing system. This was developed under H_∞ performance characteristics for improving the robustness against the variations in the turbine system like damping coefficient and reference pressure. The performance of the proposed governor controller was compared with the existing proportional controller using simulation results. The proposed controller performed very well for disturbance rejection as well as for speed tracking. The novel controller designed was attached to the steam unit in Damavand power plant and its frequency tracking ability in conditions of reference pressure variations were examined. The system response showed the robustness of the proposed controller. However other methods could be explored to improve the time domain performance simultaneously with robustness.

Mohamed *et al.* [15] investigated the design of self tuning of a PID controller for an isolated turbine system. The PID controller of the model was tuned using adaptive fuzzy control. The same model was redesigned using GA, PSO and ANFIS methods. The genetic algorithm used optimization method in which the system overshoot was defined. This technique was further modified using Particle Swarm Optimization method (PSO). Further Bacterial Particle Swarm Optimization (BPSO) was used for velocity updating and position updating of particles reinforced by two bacterial behaviors. An adaptive neuro fuzzy inference system (ANFIS) a cross of ANN and Fuzzy Inference System (FIS) was designed. Simulation was done after using adaptive methods for PID tuning. The designed PID with Adaptive Fuzzy logic showed a better response than the PID designed with other AI methods in terms of rise time and settling time. BPSO showed better responses than PSO and other GA techniques. ANFIS showed better performances in BPSO than other AI algorithms.

Approximate transfer functions were used in the model of the turbine system in plant. Hence use of more accurate models was required.

T.R Rangaswamy *et al.* [16] proposed a novel design for combustion control of a utility boiler of a 210 MW thermal power plant using model reference fuzzy adaptive controller. The main objective of this controller was to regulate the fuel and air ratio, to maintain the desired steam pressure at the turbine inlet, irrespective of the changes in steam demand. Existing control schemes have difficulty in coping with the time delay, uncertainties of the combustion process and frequent load changes. An experimental set up was fabricated and designed in the laboratory. Simulation studies were carried out using three control strategies, namely conventional PID, conventional FLC, and model reference fuzzy adaptive controller scheme. Detailed experimental data have been obtained from thermal power plant to validate the controller's performance. There was no offset in the steady state output. The controller output was smoother without any oscillations which has increased the life of the control elements. Least integral square error and Integral absolute error has revealed the superiority of the proposed controller. It was concluded that this proposed design could be applied to different utility boilers. But the systems required precise adaptive algorithms with fast data collection along and sophisticated signal conditioning systems.

Mohamed *et al.* [17] studied the control of load frequency in a two area interconnected power system with PID controllers. PID parameters were tuned using different adaptation techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and fuzzy algorithms. The tuning mechanism was first obtained for the PID controllers. The overshoots and the settling times with the proposed controllers were better in comparison to the conventional PID controllers. Simulations were carried out with system disturbances from a range of 1% to 10%. The comparison of the performance responses of the conventional PID controller with the PID controller tuned using different intelligent techniques for both the cases showed that the fuzzy tuned controller had better generalization capability, feasibility, reliability, as well as accuracy than GA & the PSO algorithms. The author concluded that the proposed controllers were very simple and easy to implement and did not require the knowledge of many system parameters. The author has however suggested the use of AI for determining the PID optimal parameters for further applications to multi area systems.

E. Yesil *et al.* [18] proposed a self tuning fuzzy PID type controller for solving the load frequency control (LFC) problem. In order to improve the transient response while preserving the steady state properties of the LFC, a self tuning fuzzy PID type controller has been proposed.

The fuzzy PID type controllers have been constructed using a set of control rules and this control signal has been directly deduced from the knowledge base and the fuzzy inference. A self tuning mechanism which adjusts the input scaling factor with the derivative co-efficient has been used. The output scaling factor corresponded to the integral coefficient of the PID type fuzzy logic controller. A two area interconnected system was considered for demonstrations. The proposed self tuning fuzzy type PID controller has been compared with the fuzzy PID type controller without a self tuning mechanism and the conventional integral controller. The proposed controller outperformed the CIC and improved the performance of the FPIDC. The author concluded that this controller designed mainly depended on the peak observer data.

Neha *et al.* [19] presented a comparative study of the Genetic Algorithm method (GA) and Particle Swarm Optimization method (PSO) to determine the optimal proportional, integral and derivative parameters for load frequency control in a single area system. A free governor operation and a load demand of 0.01 were assumed. The control objective was to eliminate the steady state error with improvement in dynamic responses. The integral of the squared error (ISE) performance criterion formulas were used to design the controller. Controller parameters K_P, K_I & K_D determined were incorporated in the LFC. Computational time of the controller developed using PSO algorithms was less than that of GA. Optimization results however were same. PI controller and GA based PID controller proved less effective in performance compared to the PID designed using PSO. This controller was simple and had stable convergence characteristics.

Sigurd *et al.* [20] presented the analytical tuning rules for PID controllers used in closed loops for various kinds of processes. The authors used IMC PID tuning rules (1986), which achieved widespread industrial acceptance. The integral terms was further modified to improve the disturbance rejection for integrating processes. Separate rules for each transfer function model were not derived. Processes approximated by first order first delay process (half method) have been used. Single tuning rules were used depending on the type of the processes. This method proved to be simple and helped in tuning the controller better. All these tuning rules were derived analytically. Rules however were general, not specific for transfer function model.

Mohammed *et al.* [21] attempted to design a fuzzy logic based PID controllers for superheat temperature control of the boiler. This superheated steam was fed to the turbines for the generation of electrical power. PID controllers were designed after the consideration of small change in temperature at the inlet as the disturbance. FL was used in the PID controller. FLC computed the change of output and added it to the previous output to get the current value. The controllers were used to get various dynamic response plots. The simulated results proved that the fuzzy logic controllers were more superior in performance compared to the PID controllers designed by Zeigler Nichols tuning rule. However, various parameters were not considered during modeling which made the results not realistic.

Non-conventional controllers. Nonconventional controllers used techniques like fuzzy logic and neural networking etc. Fuzzy Logic represents human operator language expressions providing an appropriate means to define operator regions. Inside this operating region, the processes could be represented by low order linear models whose parameters could be learned from input and output data by neural network. Neuro fuzzy methods are effective ways of modeling nonlinear systems where fuzzy rules could easily express the expert knowledge in linguistic form. Neural networks possess the learning ability for approximating nonlinear functions with arbitrary accuracy. Artificial Neuro Network provides a direct link between artificial neural networks and fuzzy systems. Optimization approaches like Genetic approach, Model Predictive approach, Particle Swarm Optimization were used to optimize the various parameters determined by the various techniques. These approaches made these controllers more effective in performance compared to conventional controllers both in terms of time and frequency domain.

Majanne *et al.* [22] developed a general predictive controller (GPC) based on Model Predictive Control (MPC) methods for a boiler turbine unit to control the pressure stability. The multivariate control problem was to achieve an optimal control of pressure stability with the valve actuator limitations and constraints. The fluctuation pressures in the actuator limits were as low as +/- 0.2 MPa in the GPC compared to 10 MPa in the PI controller actuating the inlet valve. The programming was done on Matlab. The authors presented a comparison of this controller with conventional control structures used in PI controllers. The results proved the GPC controller very effective in controlling processes with strong interactions in the process variables. Its effectiveness was proved further by replacing 6 PI controllers with 1 GPC. Tuning was based on selection of length of prediction & control horizon, cost function weighing factors & parameters of noise model included in internal model of controller. MPC controlled processes faced difficulty in stability analysis.

Keshavarz *et al.* [23] developed a discrete piece wise affine controller (PWA) for a non linear third order model of a boiler turbine unit. The PWA nonlinear model and the nonlinear model were compared at different operating zones. PWA models performed better for a larger operating range. This controller was used to balance the mechanical energy and the power demand keeping the internal parameters of pressure, temperature and drum level in a range. A comparison of this controller structure was made with the H_∞ controller structure with AWBT compensation.

PWA models with MPC showed faster out puts than the H_∞ controller, but set point tracking was faster by 50 seconds in linear control. The quantity of the control signals with robustness against the disturbance signals were the advantages obtained. Simulation results allowed the comparison of the performance of H_∞ controller and the explicit MPC. The two internal parameters namely drum pressure and drum level reached the final values faster in MPC control compared to linear control. It was observed that none of the control efforts of the explicit MPC got saturated in comparison to MPC. The simulated output showed the good quality of the control signals and robustness against the output noise. The major gap was the extreme complexity with the prediction horizon.

Jerry *et al.* [24] developed a nonlinear control system for a two stage steam turbine with a re-heater. The design was presented for the control of the opening of the high pressure and low pressure valves. A feedback linearization technique was developed for the plant model. A linear quadratic controller [LQC] was also developed with the development of nonlinear algorithms. Classic linear PI controllers were used in the same plant model. Control action was observed by the relative pressure in the two valves and the re-heater. The authors compared the performances of the nonlinear controller with a linear controller and a classical PI controller in the plant model. It was observed that the nonlinear controller performed the best in terms of least settling time with negligible overshoot. The performance of the controller was stable over the entire range of operation. The power output increased from 0.9 to 1.0 per unit with the use of nonlinear controllers. The control system developed was suitable for normal working conditions. However, it could not cater abnormal start up conditions and emergency conditions.

Chen *et al.* [25] presented modeling of plant dynamics and uncertainties for robust control of electric power generation systems under wide range operations. A 27^{th} order non linear time invariant plant model was developed for a fossil fueled generating unit having a rated load capacity of 525 MW. An integrated Feed Forward/Feed Backward FF/FB policy was synthesized based on the models of the power plant dynamics, uncertainties, and performance specifications for the load following operations of a 525 MW fossil fueled generating unit. Uncertainties in plant modeling have been identified and quantified. These uncertainties and the desired plant performance specifications are in turn represented by appropriate transfer matrices in the H_∞ based structural singular value μ. The results of the simulation demonstrated that a robust feed forward feedback control policy satisfied the specified performance requirements of power ramp up and down in the range of 40 % - 100% load under normal conditions of load.

It was also interpreted that modeling uncertainties could be reduced at the expense of the size and complexity of the plant model. This has made the synthesis and implementation of the control system difficult. However an over simplified plant model may not be adequate to meet the performance specifications. The robust control laws used were conservative to account the modeling uncertainties.

K Gooden *et al.* [26] used the model of once through steam generators (OTSG) for determining the time response characteristics of feed forward and feedback control elements for thermal mass flow and transit time lags. Input disturbances to both gas temperature and flow were considered. The aim was to minimize the temperature variation. It was observed that tight regulation of the final steam temperature with minor changes in the gas temperature and flow was more effective than the results achieved by the tuning of conventional PI controllers used. Tuning valve controllers and shaping of the filters for the signals in the feed forward algorithm were undertaken. This facilitated the valve controller to act fast. It minimized the variance in final steam temperature in the order of +/- 5 ^{0}C. Identification of transfer function models for various processes when the turbine parameters reach affected steam temperature was required. Testing of the control approach on a real OTSG is yet to be done.

R. Schuh *et al.* [27] demonstrated a non linear trajectory control for a condensation steam turbine with steam extraction in a chemical processing plant. This was done in two steps, modeling of mechanical part (rotational speed) and modeling of the thermodynamic part (extraction pressure) of the turbine. The system equations used to calculate the turbine's output depended on the inlet and the outlet states of the four turbine stages. The rotational speed and isentropic enthalpy difference were two parameters considered for determining the turbine output. A flatness based control approach involving non linear forward and feedback control was employed. This control loop achieved a decoupling of the extraction pressure and the rotational speed. The modeling errors with respect to the turbine output were counteracted by an integral control part. To account for the modeling uncertainties, a disturbance torque was introduced. This was estimated by a disturbance observer. Trajectories of both extraction pressure and rotational speed were tracked independently with high accuracy as per the simulation results. An excellent closed loop performance with the maximum extraction pressure error of approximately 0.1 bar and a rotational speed error of less than 3 per minute were achieved during the failure scenario and steady states. Parameters were identified using data provided by turbine manufacturers. This data could vary with various models.

Chen *et al.* [28] proposed a methodology for synthesizing an integrated feed forward-feed backward control (FF/FBC) strategy for wide range robust control of commercial scale steam electric plants. The power plant under consideration was a fossil fueled generating unit having a rated capacity of 525 MW. The plant dynamics were represented by a 27^{th} order non linear state space model. The control objective was to steer the plant from the initial equilibrium state of power at 525 MW (100% load) to a new equilibrium state of 210 MW (40% load) within the specified time and constraints. The objective was to facilitate the daily cycling of large electric generating units originally designed for base load operation. In the proposed control synthesis methodology, the FFC law was generated via nonlinear programming for the simultaneous optimization of all the control inputs under specified constraints. The NP problem for FFC was formulated using GA. Numerical computation was done using NP software package called NPSOL which used SQP algorithm. Runge Kutta Fehlberg was used to solve the differential equations. The family of optimized trajectories which represented the best performance of the plant under the specified conditions served as the tracking signals for the FF/FBS system. The FBS law was synthesized using H_∞ - based structure singular value approach to achieve the desired stability and performance robustness. Optimal trajectory was determined. Nonlinear constraints were easily synthesized. Robust stability and robust performance under specified criteria was achieved by μ synthesis. However, highly sophisticated software packages were required for implementing this integrated control system.

Atul *et al.* [29] considered an interconnected two area thermal - thermal power system for Automatic Generation Control of power systems to control load frequency. PID controllers were replaced in this power system by fuzzy controller**s**. The two inputs error and change in error have been converted to fuzzy numbers in the fuzzifier using five membership functions. The resultant fuzzy subset which represents the controller output has been converted to the crisp values using the defuzzifier scheme. The fluctuations in frequency were minimized in the system output. The performances of the different controllers for the variable inputs were studied & compared. This paper showed the advantages of the usage of intelligent controllers in comparison to conventional controllers in case of load frequency problems. These controllers have given good results in terms of system's robustness and reliability. The output responses of the frequency with various kinds of controllers like proportional, PI, PID and FL controller have been compared. The dynamic responses for a fuzzy logic controller in terms of rise time, settling time, overshoot and undershoot have proved the best. The optimum values could be obtained by Genetic Algorithms and Neural Network for further improvement in performance.

D.N Dewangan *et al.* [30] presented an interval type-2 fuzzy logic (IT2FLC) model for a steam turbine governing system of a power plant. The oscillations of the internal generator angles were observed for an indication of a performance of the control scheme over a wide range. The power system's transient terminal voltage and frequency stability enhancement have been investigated. Uncertainties measured by sensors are the inputs which could change due to environmental conditions (wind, sunshine, humidity & rain). Membership functions in fuzzy logic controllers called footprint of uncertainty (FOU) were formed. The performance of the proposed controllers was evaluated. An experimental set up of the power system was built for the verification of the IT2FLC. Responses for load change for different types of controllers have been compared. When the systems were tested for excitation with various load changes, output responses of the excitation system did not vary. It had an effect only on the frequency response. The IT2FLC controller developed a good generator terminal voltage profile. The transient stability response also improved. The verification was done in the experimental set up. However, a validation of this controller in real conditions was required.

Rohit *et al.* [31] developed a dynamic simulator for the supercritical coal fired unit. Coordinated control systems with all the loops having conventional controllers were developed for this unit. Later some loops were considered to be nonlinear. These loops were identified and suitable nonlinear models were developed for them based on energy balance relationships. A Generic Model Controller was implemented for the steam temperature control. The coordinated controller with non linear models performed better than the controller with conventional controller loops for both steam temperature control and throttle pressure control. Experimental demonstration was required to prove the actual utility of these nonlinear models. Techniques like neural network have been suggested for further improvement. The nonlinear models used were phenomenological models not accounting all the possible disturbances that could hit the system.

Ratnesh *et al.* [32] presented the design of a fuzzy controller for load frequency control in power system operations. The work has been done for a two area Thermal –Thermal System and for a Thermal – Hydro system. The control objective was to regulate the frequency of the two areas. Each area has been represented by a turbine, generator and a governor. Comparison of simulation results have been made with the PI controller used in Thermal & Thermal system with the fuzzy controller newly designed. The steady state error was zero in both cases. The settling time reduced from 11s – 7s. The peak overshoot minimized from 0.05% to 0.02%. In the case of the Thermal –

Hydro power plant comparison of the simulation results of the PI controller with the fuzzy controller, showed zero steady state error for either cases. The settling time reduced from 23s to 17s. The overshoot reduced from 0.02 to 0%. These results proved the improvised dynamic performance of the fuzzy controllers designed. However controller performance totally depended on the characteristic parameter estimated from the plant online.

Badam *et al.* [33] developed a fuzzy MPC for optimal load cycling of steam turbines. During the process of cycling, large thermal stresses were induced in boilers and turbines especially in the rotors of the turbines where the load rates are limited. Equipment service life was reduced and the maintenance cost was increased. The control objective was to meet the demands at minimal cost with the available generation equipment. Two methods namely fixed and sliding boiler pressure control were used. In the fixed mode, the governor valve was used to control the output, while the pressure was constant. Load changes followed at the expense of large thermal stresses developed due to inlet steam temperature fluctuation. In the second mode, the boiler pressure controlled the output power when the turbine governor valve was kept open. Here thermal stress was minimized due to slow expense of power. Fuzzy logic was used to determine priority amongst conflicting performance objectives like good load tracking with minimum thermal stress. A cost optimization was the result. MPC was further used to optimize the required optimal load against the minimum stress taking the long term performance into consideration. A comparison of the fuzzy MPC with a fixed and a variable pressure controller was also presented. For a steep load cycling, the variable pressure controller caused poor load tracking with a constant pressure inducing a high thermal stress. It was observed that the fuzzy MPC performed better using the fuzzy rules inducing minimum stress and maintaining good load tracking. As complexity in model increased, requirement of higher level controllers containing explicit trade off knowledge regarding degree of compromise among competing control goals as performance versus safety, fuel efficiency versus emission were needed. Evaluation of rules after every iteration, was done offline to reduce response time and decrease the memory requirements and implement an inexpensive FLC.

Wang *et al.* [34] established a mathematical model based on the immune system's wavelet network. A new approach has been presented for on line diagnosis. The mapping relationship of the relative internal efficiency of the low pressure cylinder of condensing steam turbine was considered during modeling. This relation can be used for calculating the relative internal efficiency of low pressure cylinder of 300MW steam turbine. The wavelet network considered was a type of neural network structure which took advantage of the wavelet function as an activation function. The wavelet space was considered as a spatial space and a relationship between the wavelet transform and the network parameters was through radioactive transforms. In comparison with the conventional network, the wavelet network not only has the right connection but also had the optimized translation and scale parameters of the wavelet function. The total error in the network was evaluated using the optimization wavelet function. The fitness function was evaluated for the antibodies. Then the immune modulation was conducted to the antibodies based on the concentration. New antibodies were again generated and the process was repeated. The proposed model featured swiftness, high precision and good generalization ability. This was a new approach to online diagnosis of steam turbine. However these algorithms were partial searching algorithms with the disadvantage of slowness of convergence rate and were sensitive to initial parameters, thereby restricting the network application to certain areas only.

S.C Tripathy [35] *et al.* described a design technique based on the Z- transform for a real time speed governor of a speed turbine. The digital speed governing system was designed satisfying main operational requirements including stability and time domain specifications. The model constituted a reheat steam turbine driving an a.c generator. The control input to the turbine was the steam through the governor valve opening. The outputs to be controlled were the electrical power and speed. The overall digital control system constituted D/A converter accepting the analogue input variables from the signal conditioning circuit connected to the turbine generator system. This produced a digital signal for processing the microcomputer. It also consisted of an electro hydraulic servo system for operating the governor valve. The design of a discrete digital controller was begun by determining the order of the controller based on the comparison between the order of the process model and the required response order. Accordingly a second order was chosen for the controller system. Its performance was tested in practical, using a scaled model of an alternating current generator in the laboratory. The governor was implemented in software on a microcomputer. Governor tests were conducted by changing the reference input signals. The transient response was obtained under different operating regimes proving the success of the design. The designed controller was physically realizable and was capable of providing the requirements of 20% overshoot and 5s settling time. The control program execution time was approximately 2ms which was less than 50ms sampling period. This demonstrated the scope of using a microcomputer for the turbine speed governing system. However this controller requires to be validated in actual systems.

III. SUMMARY OF LITERATURE REVIEW

A brief summary of the literature review is presented in tabulated form as a ready reference, Table 1.

Table 1: Summary of Literature Review.

Ref No	Objective	Controller	Method/ Technique	Advantages	Limitations
[6], [12], [15], [20]	Tuning for robustness &speed control.	PI, PID	GA, Taylor's approximation Adaptive Fuzzy logic.	(i) Freedom of defining optimal criteria and high accuracy. (ii) Improved performance. (iii) Ease in implementation with Simple logic.	(i) Tuning has to be carried offline High accuracy led to slow convergence. (ii) Required accurate model representation & larger Settling time.
[1], [14], [27], [35]	Torque /Speed control	P, PID, FF/FB.	Feedback linearization, linear matrix inequality (LMI), A/D converter, Flatness based control	(i) Simple and easy to implement (ii) Robustness improved inspite of variations in the damping coefficient & reference pressure. (iii) Improved transient response under different regimes. (iv) Desired trajectories of both extraction pressure and rotational speed were tracked with high accuracy.	(i) Reduced order transfer functions (ii) Other methods could be explored to improve the time domain performance simultaneously with robustness. (iii) Model uncertainties and nonlinear friction was counteracted by compensations.
[8], [16], [22]	Pressure control	PI, fuzzy PI, PI with GPC, PID with FLC & MRAC	Neuro-Fuzzy Network, Model Predictive Theory, adaptive controller approach.	(i) Efficiency of system was improved by overcoming various disturbances. (ii) GPC controller was very effective in controlling processes with strong interactions in the process variables. (iii) The output was smooth which increased the life of the control elements. (iv) User friendly and maintenance free method. (v) MRAC design could be applied to any type of utility boilers.	(i) MPC processes faced difficulty in stability analysis. (ii) Control schemes have difficulty with the time delay and non linearity due to the uncertainty of combustion & load change. (iii) MRAC required precise data. (iv) MRAC needed sophisticated signal conditioned systems to perform.
[23]	Pressure temperature & Drum level	Piecewise Affine (PWA), MPC & H_∞	MPC theory & H_∞ robustness theory	(i) PWA with MPC showed faster out puts than the H_∞ controller, but set point tracking was faster in linear control. (ii) Easy implementation over several regimes. (iii) Good robustness against the output noise.	(i) As the input and out weights of parameters is increased with sampling time, the problem becomes complex making the prediction difficult for Model Prediction Controller.
[21]	Temperature Control	PID, FL PID, PI, FB/FF, GMC	Mamdani Inference system, Feedback linearization, Generic approach	(i) Superior in performance compared to the conventional PID controllers designed by Z-N rule. (ii) Minimized the variance in steam temperature (iii) The controller having all non linear models performed better than the conventional controller.	(i) Parts of the power system used low order models. (ii) Experimental demonstration was required to prove the utility of these nonlinear models.
[24]	Valve opening	PI, LQ-FB	Feedback linearization, linear quadratic.	(i) Nonlinear controller performed better in terms of settling time & overshoot. (ii) The performance of the controller was stable over the entire range. (iii) The power output increased.	(i) The control system was suitable for normal working conditions and could not cater to abnormal start up and emergency conditions.
[2], [3], [4], [5], [7], [10], [11], [17], [18],	Frequency	PI, FLC, I, FGPI, PID, PD, H_∞ PI, GA PID, PSO PID	FL,FL based PID, FB, linear time invariant model, GA, PSO	(i) The overshoot, settling time & frequency deviation reduced in fuzzy control compared to PI control. (ii) Fuzzy control has better satisfactory generalization capability, feasibility and reliability compared to GA and the PSO algorithms.	(i) Experimental demonstration was required to prove the utility of these nonlinear models. (ii) Transient response could be unstable because of abruptness in system parameters. (iii) LTI models are required for accurate operation.

Ref No	Objective	Controller	Method/ Technique	Advantages	Limitations
[19], [29], [31] [32]				(iii) Overshoots of PI controllers were reduced with Generation Rate Constraint Controllers. (iv) PID controllers performed the best compared to PI & I in terms of settling time. (v) Use of H_∞ & reduced models reduced the overshoots. (vi) Lesser settling time was obtained with the introduction of gains. (viii) Self tuning improved the performance of the controllers. (ix) These controllers were robust and reliable. (x) PI and GA- PID controller proved less effective than PID using PSO. (xi) Computational time was less.	(iv) The dynamics of the power system is nonlinear, time invariant and required the use of AI. (v) Results needs to be tested for vigorous conditions in more accurate descriptions incorporating the nonlinearities in the model. (vi) Continuous requirement of optimizing the P & I constants to achieve a stable response as the disturbance varied. (vii) The controller depended on the peak observer idea. (viii) Controller performance totally depends on the characteristic parameter estimated online from the plant. (ix) Assumptions of a free governor operation and a load demand of 0.01 could vary.
[25]	Stability & Robustness	FB/FF	Feed back with H_∞, FFC	(i) A robust FF/FB control policy satisfied the performance under normal conditions. (ii) Optimal trajectory was determined. (iii) Nonlinear constraints were synthesized in the program. (iv) Robust stability and good performance was achieved by μ synthesis.	(i) An over simplified plant model may not be adequate to meet the performance specifications as the robust control law have to made sufficiently conservative. (ii) Highly sophisticated software packages are required for implementing this integrated control system.
[9]	Stress, Temperature Speed	PI, FLC	Fuzzy Logic.	(i) Maintained explicit trade off criteria. (ii) Managed multiple control strategies.	(i) Performance is dependent on the operator input for the options available in the model. (ii) The system inputs are influenced by the weights assigned.
[34]	Efficiency	Neural Network	wavelet networking	(i) Efficiency of LP cylinder of condensing steam turbine could be evaluated (ii) Ability of the immune network to address online diagnosis problems. (iii) Proposed model featured swiftness, high precision and generalization ability.	(i) Algorithms are partial searching algorithms. (ii) Slowness of convergence rate. (iii) Sensitive to initial parameters, thereby restricting the network application
[13]	Tracking output	PID, Adaptive (MRAC)	stable inversion & H_∞ robust method, MRAC for MIMO using Lyapunov functions	(i) In MRAC method, results have shown the disturbance rejection and robust stability of the system to non parametric uncertainty. (ii) The effectiveness was proved by introducing six uncertain parameters on a proposed model. (iii) Quick response in MRAC without overshoots.	(i) Not applicable to non linear boiler turbine with time delays.
[33]	Optimal load cycling	Fuzzy MPC, Variable & Fixed pressure	FL, MPC	(i) The fuzzy MPC performed better using the fuzzy rules inducing minimum stress. (ii) Good load tracking maintained.	(i) Hardware implementations are expensive (ii) Increased response time.

IV. CONCLUSIONS

Conventional controllers developed for thermal power plant are P, I, PI, PD & PID. The performances of these controllers have been enhanced using Fuzzy Logic, Neural Networking etc for obtaining the PID parameters. As a result, fuzzy PI, fuzzy I, fuzzy PID controllers etc were obtained. These controllers retained most of the classical features of conventional controllers simultaneously gaining the advantages of nonconventional techniques.

Non conventional controllers however was developed using nonconventional approaches. The controller was developed using Fuzzy Logic, Neural Networking, Multi Layer Perception Theory, Linear Regression, Feed Forward & Feed Back approaches etc. These techniques had capabilities of generalization, could incorporate nonlinearities and performed better when load changed and there were time delays. The capabilities of these non conventional controllers have further been enhanced using optimization approaches like Genetic Algorithm, Partial Swarm Optimization & Bacterial Partial Swarm Optimization etc for getting optimal outputs desired.

Also controllers have been synthesized for nonlinear thermal plant by three methods namely Taylor's approximation, Linearization by special co-ordinate change & state feedback and Lyapunov functions. The first method was used in cases where plants were away from nominal operating points. In the second kind, linearization was done using differential equations for which standard linear quadratic controls were applied. In the third case, Lyapunov function of the plant was made dependent on the control signal. It was used in cases of feedback linearization.

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