A Survey of Recent Automatic Generation Control Strategies in Power Systems

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Abstract: An attempt is made in this article to show literature review and a latest and exhaustive bibliography on the AGC of power systems. Various control aspects concerning the AGC problem have been highlighted. AGC schemes based on techniques and parameters are discussed. The investigations on AGC systems incorporating RES, asynchronous tie-lines and deregulated environments have been analysed. Finally, AGC strategies based on variable structure, robust, adaptive, self-tuning, digital/discrete, and intelligent control have also been incorporated.

Keywords: AGC, Asynchronous Tie-lines, Power systems, Intelligent Techniques

I. INTRODUCTION

At the dawn of independence in 1947, power generation, transmission and distribution systems were mostly confined to metropolitan cities and big urban areas. These areas were controlled by the government/private organizations in India. The country had basic technological base in electrical power engineering for the development of the power sector. In these developments, India had established various types of power utilities to make the life of the people comfortable. After that the applications of electrical energy have been in many fields influencing the life of people like; farming, medical, engineering etc. As far as the dedicated applications of electrical power are concerned, most of the sophisticated equipments require good quality of electrical power for their proper functioning. The quality of power can be maintained by properly operating and controlling the operation of electrical power systems with the help of experienced power engineers [1, 2].

In recent years, the electrical power systems are in a changing phase from an integrated utility environment to deregulated environment. In the deregulated environment, competitive parties are free to purchase and sell bulk amount of power at competitive prices in open market. Moreover, different variety of equipments with larger capacity and fast power consumption, such as investigating plants for nuclear power development and iron industries, extended significantly. They may produce the frequency oscillations whenever these loads are involved in power system operation.

It is necessary to counter system frequency control services by making adequate modifications in the design of frequency control schemes. Power system operation and control in a deregulated scenario, such as automatic generation control (AGC) is an ancillary service came into a possession of a principal role to keep the reliability of electrical power system at a satisfactory bench mark, and is going to be more useful nowadays in view of to the interconnected power systems complexity. As indicated, frequency oscillations stabilization in interconnected power systems is going to be difficult task when operating in competitive environment. A modified frequency stabilization service stresses on efficiency, reliability and profits. The modern and modified controls are also fulfilling the needs of power systems operation and control which is more required in demand side as well as generation side management.

The function of AGC is to control the allocation of generation so as to maintain the frequency and net interchange of power through transmission lines under sudden varying load conditions. To operate it, digital computer based telemeter data of loadings of generators, tie-line flows and frequency values are needed. Through the concern running technologies, it then sends raise or lower commands to the generating units under control.

The main objectives of the AGC are to satisfy the following requirements:

- Zero steady state errors in tie-line power exchanges and frequency deviations.
- Optimal transient behaviors.
- In steady state, the power generation levels should satisfy the optimal dispatch conditions.

The AGC problem has been made of great value of research articles from time to time. The AGC regulators are developed to deal effectively with parametric uncertainties, incorporating area interconnections as parallel extra high voltage alternating current (EHV AC)/high voltage direct current (HVDC) transmission links and thyristor controlled phase shifters in transmission lines. The traditional optimal/sub-optimal, variable structure, robust, adaptive, self-tuning, digital and discrete mode AGC regulator designs have been addressed in the literature. In recent years, applications of genetic algorithm (GA), simulated annealing (SA), particle swarm optimization (PSO), ant colony optimization (ACO), fuzzy logic (FL), artificial neural network (ANN) and hybridization of these in the design of AGC regulators for interconnected power systems considering various types of model characteristics have also been witnessed in articles.

Apart from advances in AGC design techniques, there have been other developments during last two decades like;

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addition of renewable energy source (RES), and deregulation of power industries also posing the new challenges for power engineers to deal these changes. For the reasons, the control schemes engaged with the AGC problem have changed to settle their dynamics appropriately. Broadly, AGC schemes based on various design techniques/methods/concepts can be categorized as; classical methods, optimal and suboptimal techniques, variable structure based methods, robust control methods, adaptive and self-tuning schemes, digital and discrete mode approaches and intelligent techniques [3, 4].

II. OVERVIEW OF AGC SCHEMES

AGC of a power system may be the initial idea implemented via the flywheel governor of the synchronous machine. But this approach was found to be inadequate. Therefore, a secondary control was incorporated to the governor with the support of a signal directly proportional to the frequency deviation with its integral. This technique composes the classical approach to the AGC of power systems. Most of the research articles relating AGC of interconnected power systems were based on transmission line bias control (TLBC) method and were considered as an early development in this area [2]. The secondary AGC schemes are developed to control the area control errors (ACEs) to zero. Subsequently, a large amount of research articles, monographs, lectures and extension digital reprints have been appeared in the literature. The contents of these articles include various aspects of power system models, AGC architecture and a number of control approach used in the development of AGC schemes. The studies are largely carried out to put forward AGC regulator sketch patterns considering linear and non-linear power system models, centralized, decentralized and modal control concepts, classical, optimal and sub-optimal control algorithms. The investigations also incorporate the sensitivity features, characteristics of load and excitation control in AGC approaches. AGC techniques based on types of interconnecting inter-ties [5], area interconnection with thyristorized control phase shifter, static volt-ampere reactive compensator and HVDC transmission links are utilized in power system control. Control of DC link is greatly investigated in [6]. Further, most of the works published earlier were aimed to consider linearized power system models for the study [5, 7]. To study AGC of linearized power system models, the power system model is linearized about an operating position [7]. For small perturbations, the small signal analysis is adequate for investigating the system response. However, it is necessary to counterbalance for system non-linearity when operating over a broad margin of operating conditions.

Keeping in view the reality of the fact that the AGC schemes designed considering linearized model do not offer the desired system dynamic performance when implemented on a necessarily non-linear system under large disturbances, therefore, countable research publications on AGC incorporating the system non-linearities have been cited in [3, 4]. Due to various benefits such as huge storage space and fast computational capabilities associated with digital computers have motivated the researchers to consider discrete mode AGC schemes for power systems [4].

D. M. Patel et al. [8] dealt with AGC in power system operation with reference to the tie-line control and the requirement of reactive power and voltage regulation under normal operating conditions in the model. The influence of speed and excitation controls on system stability with suitable feedback signals is also examined. Further, they investigated the relation between frequency control and voltage control through a control loop. Moreover, a refined model was proposed to show the interaction between the load frequency control (LFC) and the automatic voltage regulator (AVR) loops. The coupling effects of the AVR and LFC loops were studied by including the excitation system in system dynamic model [9]. T. W. Reddoch et al. [10] have presented a state variable model for AGC of a linear interconnected power system. The efficacy of optimal feedback controllers was compared with classical controllers.

S. Bittanti et al. [11] have derived a multi-variable control system based on frequency decoupling in plant models where the dynamics of the controlled variables were strongly interacting. Multi-variable solutions are generally led to better performance, since the plant model considered as a whole, allowing the optimization of the control action. In fact, the classical systems were preferred since they allowed the operator to use his experience when necessary, acting manually on single parts of the plant model. The design of a multi-variable control system that corrected the action of classical regulation allows both optimal performance and maximum flexibility.

I. Egido et al. [12] have discussed discrete time non-linear model of a thermal unit for the development of AGC regulators. The non-linear block followed by linear one consists of a governor dead band and a load change rate limiter, while the linear block consists of a second order linear model and an off-set. It has been found that the unit response was mainly determined by the rate limiter, while the other model components were used for a better fitting to the real response. An identification procedure was used to estimate the parameters values of the model. Also Bhatt et al. [13] proposed a traditional AGC loop with modifications incorporated for simulating AGC in restructured power system model and the concept of distribution participation matrix for power system model is used to simulate the bilateral transactions contract in the multi-area models.

III. AGC BASED ON CONTROL TECHNIQUES

During the last four decades, considerable interest has been shown towards the application of optimal control theory for arriving at more efficient AGC regulators for interconnected power systems. A number of methods have been developed using optimal regulator design approach and various analytical techniques to evaluate this problem with smooth control. But, sometimes power systems do not have all the system states, means some useful measurements are missing in the operating time. This type of AGC problem can be solved by the implementing of observer technique based controller in which all the states are redesigned. However, the sub-optimal control technique creates the necessary solutions for the AGC problem without reconstruction of all the system states, and it can easily solve the AGC problem with insufficient system states.

In [2], Elgerd and Fosha have exhibited their pioneering work on optimal AGC regulator design using modern control concept. A two-area interconnected power system consisting of two identical power plants of non-reheat thermal turbines was considered for investigations. Tacker et al. [14] have investigated two-area interconnected power system model with optimal AGC regulators. K. Yamashita and T. Taniguchi [15] have analysed AGC problem for interconnected systems considered from the viewpoint of optimal control theory. However, other algorithm was derived by M. L. Kothari and J. Nanda [16] for AGC regulators of an interconnected hydro-thermal power system using a performance index that circumvents the need for a load demand estimator. Moreover, K. P. S. Parmar et al. [17] have developed dynamical response of the AGC problem in an interconnected reheat type power system under consideration with a practical viewpoint by designing the optimal full state feedback controller and also Ibraheem and P. Kumar [18] have dealt a computational approach for the solution of the Matrix Riccati (MR) equation for optimal full state feedback control, and then weighting matrices 'Q' and 'R' of state feedback optimal control strategy was proposed by Mariano et al. [19]. Later, they [20] addressed the stabilization and performance of the AGC regulator by using the theory of the optimal control.

M. Nakamura and H. Hatazakia [21] have developed an optimal control theory based AGC regulator for hydro-thermal power system model in the summer and rainy season. At that time various schemes of AGC were employed, for example, flat frequency control, flat tie-line load control and tie-line load frequency biased control.

M. A. Abdel-Halim et al. [22] have described a technique for designing an optimal LFC regulator for a power system whose dynamical equations contain a backlash element. The approach has been applied to the problem of LFC for a single area steam power system. Besides H. G. Kwatny et al. [23] have explained the optimal AGC formulation as a tracking problem in which energy source dynamics and load play a central role. It is shown that load prediction and coordination of area generation in a multi-area interconnection can effectively improve the regulation of inter-area power flows. Later, an optimal sampled data controller designed with time-multiplied performance index (PIx) based on dynamic programming for the optimal AGC problem of a power system investigated by A. Kanchanaharuthai [24]. This sampled data AGC regulator was used in order to achieve not only in improving faster dynamic response, such as the incremental frequency deviation, but also in extending the structure of sampled data optimal AGC regulator from the standard optimal PIx to the case of time-multiplied one.

However, the optimal controller design requires the measurement of all the state variables for their feedback. This is a serious limitation because of the fact that measurement and access of all the state variables is not possible all the times. A pioneering work by V. R. Moorthi and R. P. Aggarawal [25] on sub-optimal and near optimal control of AGC system was presented. The sub-optimal and near optimal control of a AGC system and later, the investigations on sub-optimal regulation of non-linear AGC system are presented by V. R. Moorthi and R. P. Aggarawal [26].

Another work was based on the concept of reconstruction of unavailable states from the available outputs and controls using an observer technique were appeared in [16]. Subsequently, LFC using reduced order models and local observers have been developed by A. Feliachi [27] for controlling the plants. Also, design of observer based decentralized LFC for interconnected power systems have been investigated in [28].

A. Rubaai and V. Udo [29] have proposed an adaptive control scheme for LFC of multi-area power systems using the minimum-variance control concept to satisfy a variety of performance objectives. The adaptive controller synthesized on the basis of an autoregressive moving average model identified by using the recursive least square model and installed on individual subsystems. After that Y. Hain et al. [30] presented a control method for process transfer function identification and an approach for the development of a power unit's dynamic model for LFC applications. This method used a two stage control procedure which indirectly reduced both noise effects and the order of the transfer function. The Liapunov's second method like bang-bang control of speed changer position has been implemented by G. Shirai [31]. E. V. Bohn and S. M. Miniesy [32] introduced an optimum AGC sample data control technique with randomly varying system disturbances.

IV. AGC SCHEMES INCORPORATING SYSTEM PARAMETRIC UNCERTAINTIES

Practically, the power system parameters do not remain constant and may vary with operating conditions such as aging, uncertainties and errors in measurement or simplification in the mathematical modelling. The implementation of optimal controllers, designed with nominal system parameter values, may not give rise to the desired system dynamic performance in the wake of power system parameter uncertainties. Therefore, a due consideration of the effects of uncertainties or variations in the design of AGC schemes is inevitable.

Stability analysis and design issues of LFC schemes for interconnected power systems with a structure uncertainty satisfying the matching conditions are addressed in [33]. A simple robust decentralized control law for each subsystem has been developed on the basis of Hessenberg model and utilizing the basic concepts of both linear quadratic regulator (LQR) theory and Lyapunov stability theory. The system parametric uncertainties were obtained by varying nominal parameter values by ±30% to ±50% simultaneously and generation rate constraints are also incorporated in [34]. Later, a concept of parametric uncertainty in power systems with asynchronous tie-lines has been analyzed in [35, 36].

V. VARIABLE STRUCTURE CONTROL BASED AGC SCHEMES

Insensitivity to parameter variation can be achieved by designing variable structure AGC schemes. A special feature of the variable structure controllers (VSCs) is that they greatly improve the transient performance of the system, while keeping the steady state error at zero [37]. G. Ray et al. [38] have focussed on a decentralized VSC approach to the LFC problem. The control scheme was based on the design of proportional-integral type switching function which in turn effectively reduces the effect of constant disturbances in the input channel and specifically parameter perturbation that satisfies the matching conditions. Then, the VSC technique was further extended to quasi-sliding mode band [39]. An additional attachment of superconducting magnetic energy storage (SMES) unit along with the variable structure system (VSS) AGC regulator exhibits better dynamic performance rather than the single VSS [40].

A. Kumar et al. [41] have proposed a discrete version of a VSC for AGC of a multi-area thermal-thermal interconnected power system. The power system model has also non-linearities such as generation rate constraint (GRC) and governor dead band (GDB). In [42], VSC is applied to design AGC regulators for an interconnected power system considering GRCs.

VI. ROBUST AGC SCHEMES

The concept of robust control theory to the AGC problem of interconnected power systems has been extensively tested. The main aim of this concept is to maintain robust stability and robust performance against system uncertainties and disturbances. Utilizing this concept, many AGC schemes have been proposed time to time in the literature.

An overview of applications of robust control techniques in power systems is illustrated by L. Fan in [43]. This review has considered a variety of robust control techniques such as non-linearity H_∞, linear matrix inequalities, MR equation approaches, Kharitonov’s theorem, structured singular value theory, linear quadratic Gaussian, quantitative feedback theory and pole placement technique have been used, and an investigation is carried out for power system reliability against the uncertainties. A combination of matching conditions and Lyapunov stability theory has been adopted to implement a robust stabilizing controller of interconnected power systems with uncertain parameters [44]. In [45] the Q-parameterization method is used to design robust AGC regulators while the set of all robust controllers of the power system was characterized by a parameter free ‘Q’ matrix. This free parameter is chosen to satisfy robust stability and other design requirements. A decentralized robust AGC scheme for interconnected uncertain power systems based on the Hessenberg Form has appeared in [33].

VII. ADAPTIVE AND SELF TUNING SCHEMES FOR AGC SCHEMES

An adaptive control and self-tuning have been a topic of research for more than a quarter of a century. These control techniques have been widely used in power systems to have power system operation less sensitive to variations in system parameters.

An adaptive control scheme based on back stepping theory is proposed for improving load adaptability of boiler-turbines for wide range operation in [46]. K. Yamashita and H. Miyagi [47] proposed a method of designing a multi-variable self-tuning regulator for an AGC scheme with the incorporation of interaction of voltage on load demand and for an interconnected power system based on least squares technique [48].

Adaptive output feedback controller for LFC of power systems has been explained in [49]. Also, oscillatory stability limit enhancement by adaptive control rescheduling was emphasized in [50] by P. R. Bijwe et al. Apart from L. R. C. Chien et al. have addressed the estimation of β for adaptive frequency bias setting in AGC [51]. Spanish AGC scheme using an adaptive gain controller is investigated [52]. Moreover, a decentralized adaptive control scheme guaranteed that the fluctuations of the load frequency control converge to a range, which can be made very small rather than centralized scheme [53] and self-tuning control performance standards controller based on Q-learning method was proposed by Y. Tao and Z. Bin [54]. The on-line estimate of system parameters for adaptive tuning on AGC is proposed in [55]. Following these, R. Prakash and R. Anita [56] have proposed a robust model reference adaptive PI control scheme. The frequency relay with consideration of load and power system dynamics is analyzed in [57].

S. C. Tripathy et al. [58] dealt with AGC employing self-tuning adaptive control for both main AGC loop and SMES. Then, multi-area AGC simulator comprising the dynamic as well as the static solutions of an interconnected power system has been utilized [59]. Subsequently for self-tuning AGC, multilevel adaptive approach was proposed in [60]. Later, PI adaptation for AGC of power system with consideration of GRC was examined by C. T. Pan and C. M. Liaw [61].

VIII. DIGITAL/DISCRETE MODE BASED AGC

Digital control scheme is more accurate and reliable, compact in size, less sensitive to noise and drift and more flexible. Optimum setting of the parameters of AGC can be obtained more realistically by formulating the dynamic model of the controller in the discrete mode. Whenever the tie-line power, frequency and generator power outputs are usually measured periodically at an interval of approximately one second and combined with desired interchange and scheduled frequency to obtain ACE, and then this technique is very fruitful. Some researchers have emphasized their attention on proposing digital/discrete AGC control schemes [62-68]. In the evaluation of AGC, the time domain investigations of the power system process and control logic are practically essential.

A comprehensive procedure for designing digital/discrete mode optimisation based AGC regulators using an integral square error (ISE) criterion was suggested by J. Nanda et al. in [63], and the ACE is introduced in discrete mode for AGC of a two-area reheat thermal system in [64]. An AGC scheme based on discrete time variable function with power demand estimation is proposed [65], and microprocessor based LFC was investigated in [66]. Then, K. Vrdoljak et al. [67] examined a discrete time sliding mode LFC of power systems delay in input. T. Hiyama [68] has investigated discrete mode optimal AGC of power systems by considering GRC.

IX. AGC SCHEMES INCORPORATING RENEWABLE ENERGY RESOURCES

Increasing demand for electrical energy, limited amount of fossil fuel storages, and increasing concerns to environmental things required for a fast development in the area of RESs. Some latest studies which explain the impacts of battery energy storage (BES), capacitive energy (CE), SMES, wind turbine (WT) and photo voltaic (PV) power generation on the dynamic performance of the AGC system [69-75].

L. Mengyan et al. [69] have presented the studies on tie-line power with a large scale wind power. A robust controller has been designed incorporating SMES for stabilization of tie-line power oscillation in the interconnected power systems with wind farms [70]. Furthermore, an application of small rating CE storage units was utilized for the improvement of AGC performance of a multi-unit multi-area power system including GRCs [71]. Later, R. Oba et al. [72] have investigated the influence of RESs such as PV or wind farms in the three-area power systems to suppress the short term disturbances with the help of proportional-integral-derivative (PID) structure based LFC considering different characteristics of power plants. An AGC scheme for grid connected MW class PV generation system is proposed in [73] while a control scheme for the hybrid photovoltaic-diesel single-phase autonomous power system is described in [74].

X. AGC SCHEMES CONSIDERING ASYNCHRONOUS INTERCONNECTION

Majority of research work presented by the power researchers regarding the AGC of interconnected power systems is limited either to two-area or multi-area power systems considering the system interconnection with AC tie-line only. As the load demands are increasing every day, the power researchers are motivated to concentrate their attention to generate and transmit huge amount of electric power through HVDC system economically, efficiently and effectively. The commissioning of an HVDC link in parallel with AC link, as area interconnection, has been gaining momentum due to its numerous advantages over the EHV AC lines. Few articles on AGC of interconnected power systems considering parallel AC/DC links as area interconnection are available in literature [36, 76-81].

Ibraheem et al. [36] have investigated dynamic performance of two-area interconnected power system considering parallel AC/DC links as area connection. The optimal AGC regulators are designed based on optimal control theory and unity rank control concept. They considered variations in the parameters associated with power transmission system, synchronizing coefficient of AC tie-line and time constant associated with DC link. Besides Z. B. Du et al. [77] have investigated a structure preserved power frequency slow dynamics, two-area having four-machine and Institution of Electrical and Electronics Engineers (IEEE) 30-bus simulation model for interconnected AC/DC power systems. The AGC scheme is set to be applied to study relevant emergency control in the future so that the bulk system viability crisis caused by load frequency slow dynamics can be released.

The concept of area centre of inertia is used assuming an uniform frequency in each control area similar to that of the traditional single-area dynamic load flow calculation. Using this concept, authors have developed area centre of inertia based back stepping sliding-mode method for emergency frequency control of interconnected AC/DC power systems [78]. It provide inter-area power support to the load disturbance in control areas through the intact interconnecting structure under emergency conditions, when the normal AGC was suspended to avoid worsening frequency stability. With the assumption of area centre of inertia frequency and the employment of wide area measurement system, the control strategy was driving the area centre of inertia frequency to track the overall system area centre of inertia frequency by virtue of coordination control of emergency generation. The AC dynamic of the rectifier subsystem was quantitatively analyzed based on the eigenvalue analysis method and robust decentralized LFC in coordination with frequency controllable HVDC links was investigated in [80].

XI. AGC SCHEMES IN DEREGULATED POWER SYSTEM ENVIRONMENT

In the latest developments, major changes have been incorporated into the structure of electric power utilities all around the world. The reason for this was to improve efficiency in the operation of the power system by means of deregulating the industry and opening it up to private competition. In restructured power system, engineering aspects of planning and operation have to be modified accordingly. The essential corresponding requirements for the proper and effective operation and control are assigned to every user operating/involving in the new operating environment are guided by independent system operator and fall under ancillary services. Among these, one of the ancillary services is the AGC. Various control aspects concerning the AGC problem have been appeared in literature [82-89].

AGC issues and control aspects in power system operations after deregulation are discussed in [82, 83, 85]. Later on, optimal output feedback method for multi-area AGC in deregulated environment was presented by J. Sadeh and E. Rakhshani [84]. H. Shayeghi et al. [86] have derived a robust decentralized controller based on mixed H_2/H_∞ control technique for the solution of AGC problem including SMES in a deregulated electricity environment. The modelling and simulation of static synchronous series compensator (SSSC) and thyristor controlled phase shifter (TCPS) in a two-area power system for AGC in deregulated environment was examined in [87]. K. Chatterjee [88] has proposed AGC in a deregulated power system considering BES system including the effects of GRC and GDB. Basic AGC in deregulated power systems of Norway and Sweden incorporating DC link and rump following controller supported by manual control was proposed in [89].

XII. AGC SCHEMES BASED ON INTELLIGENT TECHNIQUES

Artificial intelligence that achieves expert level competence in solving the problems by bringing knowledge about specific tasks is called knowledge based or intelligent systems. Perhaps AI was first proposed by E. A. Feigenbaum et al. in the early 1970s [90]. Artificial intelligence (AI) constitutes intelligent technique based methods in which they approach to knowledge or rule based system algorithm, which uses the knowledge and interface procedure to solve problems that are difficult enough to be solved by human expertise. Main advantages of intelligent techniques are:

- It is permanent and consistent
- It can be easily transferred or rectified

- It can be easily augmented

AI techniques started with simplified scheme and extended to more and more modern techniques such as object oriented design, qualitative reasoning, verification and validation methods, natural languages and multi-agent systems. For several years, a great deal of intelligent technique applications has been developed to prepare plan, analyze, manage, control and operate various aspects of power generation, transmission and distribution systems. Intelligent technique has also been implemented in many applications in the power systems like generation scheduling, price forecasting and other technical problems.

Intelligent techniques have also shown to overcome the unpredictable dynamics, computational complexity and problems associated with large scale distributed complex power plants. K. Y. Lee [91] has demonstrated the developments in power plant control in earlier years by seeking techniques other than classical PID controls. This panel introduced intelligent techniques to the power plant control, which deals with complex dynamic systems having significant uncertainties.

Moreover, recently intelligent approaches i.e. GA, SA, PSO, ACO, FL and ANN etc. have been applied for optimal AGC regulator design techniques. These are very effective techniques with their origins rooting into the nature. These approaches have been shown to provide near optimal solutions in linear/nonlinear and continuous/discontinuous environments. These approaches have been implemented by the researchers in various types of AGC problems. The implementation of hybrid techniques gives the ameliorated dynamic performance of the systems because these approaches can search global solutions in the present problem of the AGC. So, hybrid techniques are also investigated in the literature.

Genetic Algorithm based AGC Schemes

GA is totally inspired from survival of the fittest theory based searching technique. GA is a near to global optimization method. It creates the pattern of solution after the natural processes of genetic recombination. In literature, a considerable number of research articles are appeared discussing the various aspects and salient features of GA and its potential application areas [92-94]. The articles relating to applications of GA to deal effectively various operational and control problems of power systems are also witnessed [95-100]. Few papers are specifically dedicated to propose design of AGC schemes of power systems [101-107].

Due to its inherent novel features, GA has been found at centre place for its application in designing optimal AGC regulators for isolated as well as interconnected power systems. Many researchers have focussed their attention to consider GA as a promising tool to optimize feedback gains of AGC regulators for power systems. The ISE and integral time-multiplied absolute error (ITAE) performance indices are considered for searching optimal gains of the controller parameters using GA technique [101]. A two-area non-reheat thermal power system was considered to exemplify the optimum parameter search by GA optimization process [102]. H. N. Al-Duwaish and Z. M. Al-Hamouz have proposed the selection of the VSC feedback gains using GA in [103]. They have demonstrated the superiority of the proposed selection method over the trial and error method to determine the optimal gains of AGC regulators based on VSC concept. The GA controller consists of two crisp inputs namely; deviation of frequency and the derivative of frequency deviation. The output of the GA based AGC regulator was the control input to each area [104]. A GA for parameter optimization of PID sliding mode LFC used in AGC of multi-area power systems with non-linear elements is proposed by L. Pingkang et al. in [105]. The method has merits of both PID and sliding mode control. A real coded GA is adopted for the optimization of PID parameters.

In [106], GA is used for the optimization of integral gains and bias factors for AGC of a three-area power system operating in deregulation environment. The conventional three-area AGC system is modified to take into account the effect of bilateral contracts on the dynamics. The performance of the system is studied for different operating conditions. A real coded GA is used to optimize the AGC regulator parameters. Another design of multiple power system stabilizers (PSS) for multi-area AGC system in deregulated power system scenario is proposed in [107]. The optimal parameters of the PSS are obtained employing GA using ITAE criteria. A two-area non-reheat thermal system is considered to exemplify the optimum parameter search.

Simulated Annealing based AGC Schemes

In a large combinational optimization problem, an appropriate perturbation mechanism, cost function, solution space and cooling schedule are required in order to achieve an optimal solution from SA. This technique is impressive in network reconfiguration problems for large complex distribution systems and its evaluating capability becomes more significant as the size of the system increases. Moreover, the objective function with a refining strategy enables this technique to escape more easily from local minima and to reach speedily to the vicinity of an optimal solution.

The benefits of SA are its general applicability to deal with arbitrary systems and cost functions. It has ability to refine optimal solution and implementation simplicity for more complex problems. The major drawback of SA is repeated annealing. This method can't tell whether it has achieved optimal solution or not. Some other methods e.g. branch and bound are required to circumvent these. The literature survey shows many applications of SA in power systems considering various aspects of power system planning, operation, control and protection etc. [108-111].

Three optimum adaptive variable-structure controllers are designed for LFC of an interconnected power system. A suitable cost function based on Lyapunov theory of VSC is used to convert VSC gains computation problem into an optimization problem. The proposed approaches are able to determine the controller gains systematically and adaptively in a step-wise fashion using simulating annealing, a well known robust optimization technique. The proposed approaches are applied to the power system subjected to disturbances variation and parameters change with the presence of the system inherent nonlinearity have demonstrated favourable effect on system dynamic performance [110]. Moreover, they are able to maintain robustness while reducing the chattering effect in VSC at the same time fulfilling the LFC requirements.

C. S. Rao et al. in [111] have proposed AGC scheme of a two-area interconnected hydrothermal system with TCPS in series with the tie-line under open market system. The gains of integral controller are optimized employing simulated annealing technique. For open market power system operation, traditional AGC scheme of a two-area system is modified to take into account the effect of bilateral contracts on the dynamics. The proposed AGC scheme found effective in stabilizing the system frequency and tie-line power oscillations by controlling the phase angle of TCPS which is expected to provide a new ancillary service for the future power systems.

Particle Swarm Optimization based AGC Schemes

PSO approach is developed through the natural inherent behavior of birds flying and fish schooling. The most attractive quality of the PSO approach is its simplicity as it involves only two main reference equations. Each particle coordinates present a possible solution assisted with two real vectors; position and velocity. The number of particles or possible solutions of a swarm can go forward through the feasible solution place to explore optimal solutions. Each particle modifies its position based on its own best exploration, and overall experience of best particles. There has been a growing interest of researchers in exploring the possibilities of developing various PSO based optimized models for their applications in various fields of interest. During the last decade, considerable attention has been shown by the scientists to present the salient features of PSO and its applications [112-116]. The PSO techniques are preferred for power system optimization [117-126]. Besides, the power engineers working in the area of power system control have used this technique for developing AGC schemes of interconnected power systems during the last decade [127-142].

W. Luo and Y. Shi [127] have applied PSO algorithm to design AGC schemes of interconnected power system incorporating control performance standard (CPS) as laid down in [128]. In [129, 130] a coordinated AVR-PSS and AGC scheme using PSO technique is developed for power system. The implementation of this scheme has resulted in an improved dynamic stability of the power system. S. K. Gautam and N. Goyal [131] have reported an improved PSO based LFC of a single area power system. The various parameters of an integrated power system are optimized through a novel craziness based PSO with wavelet mutation in [132]. Subsequently, R. Hemmati et al. [133] have reported PID controller gains adjustment using PSO for AGC system of a multi-area interconnected power system. The design of a robust PID controller for LFC of non-minimum phase hydro power plant is presented using PSO enabled automated quantitative feedback theory which was developed by B. Satpati et al. [134]. Furthermore, the optimal AGC controller parameters search technique was formulated as an optimization problem with a standard infinite time quadratic objective function in [135].

K. R. Sudha et al. in [136] have addressed PID controller design of non-linear systems using an improved PSO approach. The effects of non-linearities like GDB and GRC on system dynamic performance are also investigated. The PSO based gain scheduling of PI control strategy is suggested for AGC of the two-area thermal power system with GDB non-linearity in [137]. In the scheme, the control is evaluated as an optimization problem, and two different cost functions with tuned weight coefficients are derived in order to increase the performance of convergence to the global optima. One of the cost functions is derived through the frequency deviations and tie-line power changes. The other function is based on rate of changes which can be variable depends on the time in these deviations. These weight coefficients of the cost functions are then optimized as the controller gains. The craziness based particle swarm optimization algorithm is preferred to optimize the parameters, because of convergence superiority. A PSO based model predictive control scheme has been investigated through a variety of tests to understand its behavior and characteristics [138]. A predictive non-linear AGC regulator design is proposed in [139]. The optimal AGC regulators of an interconnected two-area power system, having multiple thermal-hydro-diesels mixed generating units are developed in [140]. The significant improvement of optimal dynamic performance was observed with the addition of a TCPS in the tie-line or CE storage units fitted in both the areas.

Moreover, AGC of two-area interconnected power system incorporating TCPS in hydro-thermal system operating in open market scenario has been reported in [141]. With this assertion, authors in [142] analyzed the dynamic participation of variable-speed wind turbines utilizing doubly fed induction generator (DFIG) for frequency control of an interconnected two-area power system in restructured competitive electricity market. Integral gains of AGC loop and parameters of TCPS/SMES were optimized through craziness based PSO in order to have optimal dynamic responses of area frequencies, tie-line power deviation and DFIG parameters.

Ant Colony Optimization based AGC Schemes

ACO approaches acquire idea from the action of actual ant colonies. These approaches are applied to solve the single or multiple functions. ACO techniques to some range mimic the real ant's nature. The major habits of ACO are definite feedback for recollection of desired solutions and distributed computation. It ignores premature convergence. The constructive greedy heuristic application was applied to get considerable solutions in the prior stages of the search operation. This meta-heuristic approach has proven to be very robust when applied about to global optimization problems and was favorably compared to other solution approaches such as GAs and SA techniques. ACO technique has been generally utilized in searching the minimum path for transmission network [143, 144]. In [145], C. S. Rao et al. have designed AGC system of a two-area interconnected hydro-thermal system under open market scenario using ant colony system algorithm.

Fuzzy Logic based AGC Schemes

The fuzzy logic theory was conceived by Prof. L. A. Zadeh, University of California at Berkley in 1964 while contemplating how digital computers can be programmed for handwriting recognition and expanded on traditional set theory by making membership in a set of degree rather than a yes/no situation [146]. Fuzzy logic concept can be used in many control applications of the real world. These applications can be household appliances, industries, power plants and in other fields of interests [147-153]. Specifically, fuzzy logic concept has been exploited in many ways for designing AGC schemes for single and multi-area interconnected power systems [154-179].

The fuzzy logic based AGC regulators of a single-area power system are developed to get improved system dynamic performance in [154, 155]. In [157, 158], fuzzy based integral controller are designed and implemented for controlling frequency and tie-line power flow in multi-area power system. J. Nanda and A. Mangla [159] have proposed fuzzy logic based controller (FLC) based AGC schemes of interconnected hydro-thermal system considering the system in continuous discrete mode. Other fuzzy logic based AGC schemes are given in [160-162]. The Takagi-sugeno-kang (TSK) fuzzy based approach using the linear generalized predictive control scheme was realized to implement on the system. The two-area interconnected power systems have been modeled and simulated for LFC by integration of fuzzy controller with sliding gain. The scheme has demonstrated the improved system dynamic performance specifications like settling time and peak overshoot over the classical PI control [163]. The impact of slider gain on LFC using fuzzy logic control of a two-area interconnected power system is investigated in [164]. The study of LFC using fuzzy theory for combined cycle power plant that consists of multi-power generation units is presented by K. Yukita et al. [165].

Fuzzy logic based multi-functional LFC scheme is described in [166]. Thereafter, fuzzy rule based AGC of interconnected power system with AC/DC links as an area interconnection is investigated in [167]. However, H. D. Mathur [168] has investigated the intelligent control scheme based AGC scheme for a multi-area power system interconnected via parallel AC/DC transmission links. J. Nanda and J. S. Sakkaram [169] have proposed FL based AGC of a two-area reheat thermal power system considering the effect of GRC. In [170], a decentralized AGC scheme is formulated for an interconnected non-linear power system. The study with robust LFC for uncertain non-linear power systems is carried out in [172]. The fuzzy logic approach is used for the development of LFC scheme. Fuzzy logic based gain scheduling of AGC regulators for power systems considering GDB and GRC non-linearities have been proposed in [174, 175].

Due to deregulation of power industry and wide use of communication networks in operation and control problem in power systems, there exist lot of problems in designing the AGC systems for such power systems. One of these is the non-linearity of the valve position limits. The other is random time delay with data dropouts of the communication network. These factors led to longer settling time and larger overshoot in frequency deviation of power system. Therefore, to keep system performance near to its optimum, a method combining fuzzy modeling with generalized predictive control to AGC system is proposed to optimize control quantity in real time simulations of power systems [176]. The FL has also been applied to get effective AGC schemes for power systems operating in deregulated environment [177, 179].

Artificial Neural Networks based AGC Schemes

The main advantages of ANN algorithms are: (i) It is fast (ii) It possesses learning ability (iii) It adapts to the data (iv) It is robust and (v) It is appropriate for non-linear systems modeling.

A voluminous research articles are presented in literature regarding the applications of neural networks in power system control [180-196]. The problems and their complexities connected to power system operation and control caused through the non-linearities implied in their formulation and solution are identified in [180, 181]. The ANN has been applied to obtain optimal gains of AGC regulators of interconnected power systems [182-186, 187-196]. The AGC schemes for interconnected power systems using ANN approach are described in [183, 184]. The schemes have demonstrated their superiority over the other techniques. L. D. Douglas et al. [186] have reported a new AGC methodology using ANN algorithm including non-conforming load problem. An effort has been done to enhance capability of algorithms so that they can discriminate between non-controllable short-term excursions and controllable long-term excursions. In [190], the authors have addressed the algorithms for designing AGC system. The design of AGC system is based on the reinforcement learning technique while the AGC problem was considered as a stochastic multistage decision making problem or a Markov Chain control problem.

Hybrid Techniques based AGC Schemes

In the latest advancement of this century in AI, varieties of combined intelligent control techniques have been realized to solve the power system control problems in a very effective and efficient manner by utilizing the salient features of various intelligent control concepts in a single control scheme [197-209]. S. Sun et al. [197] have presented a method to solve the decoupling problem in AGC and automatic frequency control (AFC) system. The decoupling system of AGC and AFC was decoupled using neural network which was trained by PSO approach. The hybrid PSO technique is used to obtain optimal gains of the AGC regulators. The refined GA was used to tune the membership functions and rule sets for the fuzzy logic control for a proportional-integral (PI) structure based AGC regulator of a multi-area interconnected power system in [199].

S. P. Ghoshal [200] has investigated various heuristic stochastic search techniques for optimization of PID controller gains of AGC of multi-area thermal generating plants using FL concept. These techniques are based on classical PSO, hybrid PSOs and hybrid GA-SA. During AGC of multi-area power system, a fuzzy system was used to decide adaptively the proper gains of a PI controller according the ACE and its change. To ease the design effort and improve the performance of the fuzzy-proportional-integral (FPI) AGC regulator design is proposed by hybridising a GA and PSO both [202]. In proposed technique, elites in the population of GAs were enhanced by PSO and these enhanced elites were selected as parents for crossover and mutation operations.

G. Panda et al. in [206] have proposed a hybrid neuro-fuzzy approach for an AGC of a two area interconnected power system considering system non-linearities in the system dynamic modelling. The evolutionary computation based four-area multi-units AGC has been studied in restructured power system [208]. A fuzzy gain scheduling of PI structure based AGC regulator using PSO has been proposed for multi-area interconnected power system in deregulated environment by G. Hou et al. [207]. Apart from, L. Wang and D. Chen [209] have devised and investigated AGC schemes in the Energy Management System (EMS) and power system planning for real time operation. They have developed a dynamic simulation of AGC model, load model and wind generation model using software.

XIII. CONCLUSION

This Article discusses the overall scenario of AGC schemes which have been reported in the literature. It covers the early stages of development of AGC strategies along with recent and modern technique based AGC schemes. The major approaches of intelligent techniques, like GA, SA, PSO, ACO, FL, ANN and their hybrid models for the application to design AGC of power systems are identified.

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