Chapter 2

Literature Survey on Load Frequency Control

2.1 Introduction

The early attempt in the area of load frequency control has been to control the frequency of a power system via the flywheel governor of the synchronous machine. This technique was subsequently found to be insufficient, and a supplementary control was included to the governor with the help of a signal directly proportional to the frequency deviation plus its integral. This scheme constitutes the classical approach to the LFC of power systems. The LFC problem has been dealt with extensively for more than three decades. The pioneering work by a number of control engineers, namely Bode, Nyquist, and Black, has established links between the frequency response of a control system and its closed-loop transient performance in the time domain.

The most recent advancement in this area is the application of concepts like neural networks, fuzzy logic, and genetic algorithms to tackle the difficulties associated with the design of LFC controller for the power systems with nonlinear models and/or insufficient knowledge about the system required for its accurate modeling. Apart from advances in control concepts, there have been many changes during the last decade or more, such as deregulation of power industry and use of SMES, wind turbines, and PV cells as other sources of electrical energy to the system. Due to these, the control philosophies associated with LFC have changed to accommodate their dynamics and effects on overall system dynamic performance. The present chapter covers the critical review of a wide range of methodologies of LFC controller with their salient features.

2.2. Classical Techniques

Very early works in this important area of LFC have been by Cohn et al. [11]–[15]. These works studied the static aspect of the net interchange tie-line bias control strategy, particularly pertaining to the selection of frequency bias setting. Based on static analysis, he has inferred that for minimum interaction between control areas, the frequency bias setting of a control area should be matched to the combined generation and load frequency response of the area. However, he has not considered the dynamic aspects of the load frequency control (LFC) problem. Quazza [16] illustrated non interactive control considering i) non interaction between frequency and tie-line powers controls and ii) each control area taking care of its own load variations. The investigations with large signal dynamics of LFC systems were reported by Aggarwal and Bergseth [17]. Elgerd and Fosha [18] have proposed the analysis of load frequency control (LFC) problem of a two area non-reheat thermal system. The controller gain setting has been optimized using integral squared error (ISE) technique. They have also studied the affect of variation of frequency bias setting "B" on integral gain setting and system dynamic performance. A technique based on coordinated system-wide correction of time error and inadvertent interchange was incorporated in an LFC study by Cohn [19]. Supplementary controllers were designed to regulate the ACE to zero effectively. Later on, energy source dynamics were incorporated in LFC regulator design [20]. The standard definitions of the terms associated with the LFC of power systems were finalized in [21]. Following that, suggestions for dynamic modeling for LFC are discussed thoroughly in [22]–[24]. Based on the experiences with actual implementation of LFC schemes, modifications to the definition of ACE are suggested from time to time to cope with the changed power system environment [25]–[27]. Since many presently regulated markets are likely to evolve into a hybrid scheme, and some deregulated markets are already of this type (e.g., Norway), the effects of deregulation of the power industry on LFC have been addressed through [28]-[30].

The major part of the work reported so far has been performed by considering linearized models of two/multi-area power systems [7], [13], [16], [18], [19], [31] and [32]. Later on, the effect of generation rate constraint i.e. non-linearity was included in these types of studies, considering both continuous and discrete power system models [20], [33]. Incorporating the dynamics of the energy source in LFC regulator design, Kwatny et al. [20] have proposed an optimal tracking approach to LFC, considering load to be the output of the dynamic system. The small signal analysis is justified for studying the system response for small perturbations. However, the implementation of LFC strategy based on a linearized model on an essentially nonlinear system does not necessarily ensure the stability of the system. Considerable attention has been paid by researchers to consider the system nonlinearities [34]–[37]. Tripathy et. al [37] demonstrated the destabilizing effect of governor dead-band nonlinearity on conventional LFC system. It is shown that governor dead-band nonlinearity tends to produce continuous oscillations in the area frequency and tie-line power transient response.

The investigations carried out using classical control approaches reveal that it will result in relatively large overshoots and transient frequency deviation [18], [38], [39]. Moreover, the settling time of the system frequency deviation is comparatively long and is of the order of 10–20 s. The LFC regulator design techniques using modern optimal control theory enable the power engineers to design an optimal control system with respect to given performance criterion. Fosha and Elgerd [40] were the first to present their pioneering work on optimal LFC regulator design using this concept. A two-area interconnected power system consisting of two identical power plants of non reheat thermal turbines was considered for investigations. A new formulation for optimal LFC strategy has been witnessed in [41]. The feasibility of an optimal LFC scheme requires the availability of all state variables for feedback. However, these efforts seem unrealistic, since it is difficult to achieve this. Then, the problem is to reconstruct the unavailable states from the available outputs and controls using an observer. Considering state reconstruction, many significant contributions have been made [42]–[47]. Bohn and Miniesy [42] have studied the optimum LFC of a two-area interconnected power system by making use of i) differential approximation and ii) a Luenberger observer and by introducing an adaptive observer for identification of unmeasured states and unknown deterministic demands, respectively. Exploiting the fact that the nonlinearity of the power system model, namely, the tie-line power flow, is measurable, the observer has been designed to give zero asymptotic error, even for the nonlinear model. LFC schemes based on an optimal observer, which is a state estimator with decaying error at a desired speed, using a nonlinear transformation [43] and reduced-order models with a local observer [44] have appeared in the literature. A simplified generating unit model oriented toward LFC and the method for its transfer function identification based on a two-stage procedure indirectly reducing both noise effects and transfer function order is presented in [47]. Due to practical limitations in the implementation of regulators based on feedback of all state variables, suboptimal LFC regulator designs were considered [48]–[50]. A suboptimal and near-optimal LFC concept using modern control theory is presented by Moorthi and Aggarwal [48]. Apart from optimal/suboptimal control concepts, modal control theory has also been used to design LFC regulators for power systems. The design method employing modal and singular perturbation techniques to effect decoupling of the interconnection into its subsystem components has appeared in [51]. In the method, after achieving the decoupling, local controllers for each subsystem are designed individually to place the closed-loop poles of each subsystem in some prespecified locations in the complex plane, and then, the resulting controllers are used to generate local control inputs, using local informations only. The LFC regulator design using Lyapunov's second method and utilizing minimum settling time theory has been proposed by Shirai [52]. The importance of the dominant time constant of the closed-loop systems in designing the regulators has been emphasized. The author has reported a bang-bang LFC policy based on this method.

In the early days, the LFC problem of power systems was dealt with using control strategies based on centralized control strategy [16], [18], [40], [50]. Many control strategies have been proposed on the basis of classes of disturbances [16]. Elgerd and Fosha [18] suggested a feedback and loop gain to eliminate the disturbance, and they also suggested a different feedback form to develop optimal controllers [40] for an electrical energy system. They assumed the load disturbances to be deterministic. They proposed a proportional controller, disregarding the steady state requirements and compensation of load disturbances. The main limitation of the works presented on LFC considering centralized control strategy is the need to exchange information from control areas spread over distantly connected geographical territories along with their increased computational and storage complexities. The decentralized LFC concept appeared in the power system control scenario to deal with such problems very effectively, and consequently, many research papers using this concept with continuous and discrete time system models have appeared in the literature [53]–[60]. In [56], the authors have examined the structural properties of observability and controllability for a class of interconnected power system models. The proposed scheme provides for the complete decentralization of a global state feedback control policy in the sense that the area control feedback loops are completely decoupled. Again, a class of systematic distributed control design methods based on i) distributed implementations of centralized control systems, ii) model reduction of dynamical systems, and iii) modeling of the interactions between the subsystems comprising the global control system is presented in [67]. The beauty of the design is to achieve almost identical results as obtained with the centralized one. The design of decentralized load frequency controllers based on structured singular values is discussed in [68]. Various LFC schemes based on two-level [71] and multilevel [72]–[74] control concepts have been reported in the literature. A two-level suboptimal controller has been suggested by Miniesy and Bohn. However, this approach does not ensure zero steady state error, and hence, a multilevel finite time optimal controller design ensuring zero steady-state error has been reported in [72]. The advantage of hierarchical structure is reflected in the fact that even if one of the control levels fails, the system remains in operation. A global controller, which also exploits the possible beneficial aspects of interconnections, has been applied for the LFC problem [74], and favorable results have been achieved. The reduction of control efforts required in the LFC of interconnected power systems is sought with the help of a singular perturbation approach. This can be achieved by decomposing the system into slow and fast subsystems and designing controllers separately for each of the subsystems, and the controllers are combined to yield a composite controller. Using this approach, the investigations on the LFC of large power systems are available in the literature [76], [77]. The separate controllers were designed for slow and fast subsystems and were combined in such a way that the slow subsystem always interacts with only one of the fast subsystems at a time [77]. The study also involves the effect of parameter variation and GRC. Kothari and coworkers [33], [61] have studied the LFC in discrete mode. The investigations were carried out with more realistic modeling of LFC strategy, i.e., considering that the system is operating in continuous mode and the controller is operating in discrete mode [33]. In [61], discrete mode LFC of an interconnected power system with reheat thermal plants considering a new ACE is described. The new ACE is derived from tie-line power deviation, frequency deviation, time error, and inadvertent interchanges. Optimum integral and proportional integral controllers using the concept of stability margin and the ISE technique have been obtained with conventional and new ACEs, and their dynamic performance was compared for a step-load disturbance.

An optimal LFC regulator design based on nominal system parameter values may not really be optimal for the system with parametric variations/uncertainties due to various system operating and environmental conditions, and therefore, the implementation of these regulators on the system may be inadequate to provide the desired system functioning. This could result in a degraded system dynamic performance and sometimes also in the loss of system stability. Therefore, considerable work has also been presented on LFC that considers sensitivities of the system parameter variations [62]–[74]. In the late 1960s, a sensitivity study was included in an optimization analysis to determine optimal parameter values of conventional LFC systems by Van Ness [62]. The VSS controllers have an advantage over the controllers based on the linear optimal control theory in selecting the values of the parameters in many different ways of a VSS controller. Insensitivity to parameter variation can be achieved by designing variable structure LFC regulators. Erschler et al. [64] are probably the first to investigate the LFC of hydropower systems using the VSS technique. It may be noted that the VSS controllers have improved transient response due to load disturbances in the power system. By properly selecting the parameters of the controller, the frequency deviations and tie-line powers effectively can be controlled. The research publications regarding the design of load frequency controllers for interconnected power systems incorporating the system parametric uncertainties are reported in the literature [70]–[75]. A control technique based on the application of linear feedback infinity robust controllers in the power system model to control the frequency deviations was proposed by Ismail [70]. This approach suggests that the controller response should be fast enough to offset the frequency errors due to load variations. A robust controller based on the Riccati equation approach has been proposed for the power system by Wang and coworkers [71], [72]. Later, based on a combination of the robust control approach and an adaptive control technique, a design procedure of a new robust adaptive controller was proposed for power system load-frequency control with system parametric uncertainties. The motivation of combining the robust control with an adaptive control was to use the robust control approach to deal with the small parametric uncertainties [72]. The other research contributions on decentralized robust LFC based on the Riccati equation approach have appeared in [74]. The design of decentralized robust LFC applying structured singular values is proposed by Yang et al. [75] demonstrates that when the frequency response-based diagonal dominance cannot be achieved, the structured singular values can be applied to design decentralized LFC to achieve the desired system dynamic performance.

2.3 Adaptive and Self-Tuning LFC Schemes

Apart from various LFC schemes, adaptive control has been a topic of research for more than a quarter of a century. Basically, the adaptive control systems can be classified into two categories, namely, the self-tuning regulators and the model reference control systems. The task of adaptive control is to make the process under control less sensitive to changes in process parameters and to unmodeled process dynamics. A number of articles have been reported on adaptive LFC schemes [76]–[80]. The implementation and analysis of an adaptive LFC system on the Hungarian power system has been done by Vajk et al. [77]. An adaptive controller using a proportional integral adaptation to meet the hyperstability condition requirements to take care of the parameter changes of the system was presented by Pan and Liaw [78]. A multi-area adaptive LFC scheme for LFC of power systems [79] and a reduced-order adaptive LFC for interconnected hydrothermal power system [80] are reported in the literature.

2.4 Concepts of AI Techniques

In practice, many nonlinear processes are approximated by reduced-order models, possibly linear, that are clearly related to the underlying process characteristics. However, these models may be valid only within certain specific operating ranges, and a different model may be required in the wake of changed operating conditions, or the control system should adopt the new system model parameters. The advent of AI techniques, such as neural networks, has solved this problem to a great extent. The neural technology offers many more benefits in the area of nonlinear control problems, particularly when the system is operating over the nonlinear operating range. The applications of neural networks in power system control are witnessed in [81]–[86]. A new LFC scheme to incorporate the nonconforming load problem was presented by Douglas et al. [82], in which an effort had been undertaken to develop algorithms capable of discriminating between uncontrollable short-term excursions and controllable long-term excursions. Out of the two techniques described, one was developed using a neural network algorithm for pattern recognition of controllable signals, and the other technique was based on the detection of the controllable signal in the presence of a noisy random load using a random signal probability model. Test results reveal that neural network-based LFC implementation has significant improvements over the modern LFC implementation. LFC system performance was evaluated with a nonlinear neural network controller using a generalized neural structure to yield better system dynamic performance than the individual neurons [83]. Recently, a four-area interconnected power system model with reheat nonlinearity effect of the steam turbine and upper and lower constraints for generation rate nonlinearity of hydro turbine was considered for the investigation in [85]. It has been shown in [86] that the LFC problem can be viewed as a stochastic multistage decision-making problem or a Markov Chain control problem and have presented algorithms for designing LFC based on a reinforcement learning approach.

The fuzzy logic control concept departs significantly from traditional control theory, which is essentially based on mathematical models of the controlled process. Instead of deriving a controller via modeling the controlled process quantitatively and mathematically, the fuzzy control methodology tries to establish the controller directly from domain experts or operators who are controlling the process manually and successfully. Recently, many studies exploiting the fuzzy logic concept in LFC regulator design dealing with various system aspects have appeared in the literature. In view to make the controller insensitive to system parameters change, fuzzy logic theory is also implemented by researchers extensively. Indulkar et. al [87] initially designed a controller using fuzzy logic for automatic generation control and responses were compared with classical integral controller. Chang et. al. [88] presented a new approach to study the LFC problem using fuzzy gain scheduling of proportional-integral controllers and proposed scheme has been designed for a four area interconnected power system with control deadbands and generation rate constraints. Ha [89] applied the robust sliding mode technique to LFC problem where, control signal consists of an equivalent control, a switching control and fuzzy control with generation rate constraints and governor's backlash on the other hand the fuzzy controller designed by Chown et. al [90] when implemented not only grid was controlled better but also resulted in economy. Talaq et. al [91] in their research proposed an adaptive controller which requires less training patterns as compared with a neural net based adaptive scheme and performance was observed better than fixed gain controller. Ha et. al [92] proposed an approach which combines the salient features of both variable structure and fuzzy systems to achieve high performance and robustness. Fuzzy logic controller, designed by El-Sherbiny [93], is a two layered fuzzy controller with less overshoot and small settling time as compared with conventional one. Ghoshal [94] presented a self adjusting, fast acting fuzzy gain scheduling scheme for conventional integral gain automatic generation controller for a radial and ring connected three equal power system areas. Yensil et. al [95] proposed a self tuning fuzzy PID type controller for LFC problem and satisfactory results are found when compared with fuzzy PID type controller without self tuning while E. Cam et. al. [96] in their work found the settling time and peakovershoot sufficiently lesser than conventional as well as other intelligent controllers.

Contributions considering the problem of decomposition of multivariable systems for the purpose of distributed fuzzy control was reported by Gegov [97]. The proposed decomposition method has reduced the number of interactive fuzzy relations among subsystems. The concept and development of LFC using ANN and fuzzy set theory to utilize the novel aspects of both in single hybrid LFC system design for power systems has also been proposed [98]. In recent years GA is gaining popularity for its easy searching process, global optimality, Independence of searching space and probabilistic nature. Instead of point-to-point search, GA searches from population to population. Although it has many advantages but the main disadvantage is that it requires tremendously high time [99]-[103]. Alander [104] has presented an extended bibliography of GA in power system. Magid et al. [105-106] used GA for optimizing the parameters of conventional automatic generation control systems and demonstrated the effectiveness of the GA in tuning of the LFC parameters. Dangprasert et. al [107] proposed GA based intelligent controller for load frequency control problem and results obtained provided good system characteristics. A real coded GA is adopted and integrated into MATLAB/Simulink in [108] and simulation results are found reasonable while [109] reported optimum gain setting of different type of controllers for a two area hydro system and analysis revealed that PID controllers give better dynamic responses for a two area hydro system. Abdennour [110] suggested GA to optimize the integral gain for a number of operating conditions of power system and his comparison reveals that the proposed scheme can be an attractive alternative from both performance and design point of view. In [111] is presented, two different methodologies for LFC problem one is based on H_∞ control design using linear matrix inequalities technique and second is GA optimization to achieve the same performance as that of first one. Both controllers were tested to demonstrate their robust performances. Chia-Feng Juang et. al. in [112] gave a GA based fuzzy gain scheduling approach for power system load frequency control. In [113], Ghoshal proposed a new GA/GA-SA-based fuzzy LFC scheme of a multi-area thermal generating system. The scheme is capable of evaluating the fitness of GA/hybrid GA-SA optimization by selecting a function like “figure of merit,” which directly depends on transient performance characteristics like settling times, undershoots, overshoots, and time derivative of frequency. The hybrid GA-SA technique yields more optimal gain values than the GA method.

2.5 Other LFC Schemes

The HVDC transmission has emerged on a power scenario, due to its numerous technical and economic advantages, for a large chunk of power transfer over large distances. Besides other applications, the commissioning of an HVDC link in parallel with existing ac links has shown beneficial effects from the point of view of stabilization of the system. Considerable attention has been paid to consider the damping effect of the dc system as an area interconnection between ac systems. As far as the system frequency control of power systems interconnected via a dc link is concerned, very few publications have appeared on this topic [114]–[116]. An AFRC system on an HVDC transmission utilizing the high-speed control features of a dc system, cooperating with automatic frequency control on interconnected ac systems, is developed by Yoshida et al. [114]. Later, the effects of an AFRC system on an HVDC transmission to the AFC on ac systems when AFRC is applied to a random load disturbance in a steady state. The frequency improving and reduction effects of the output power of regulating power stations by AFRC are analyzed by a digital computer [115]. A new dc AFC system, which applies a multivariable control to the dc system-based frequency control and capable of controlling the frequencies of the two ac systems optimally while maintaining their stability, is developed by Sanpei *et al.* [116]. Considerable research work on the LFC of interconnected power systems incorporating ac and dc links is contained in [117]–[121]. Investigations on decentralized robust LFC of a multi-area interconnected power system with ac as well as frequency-controllable HVDC links are reported in [118]. A comprehensive research work has been carried out by proposing optimal LFC regulators for two-area power systems with parallel ac/dc links by Kumar and Ibraheem [119]–[121]. The interconnected power systems were investigated with the implementation of designed optimal regulators by considering the incremental dc link power flow as an additional state as well as control variable. The investigations reveal that the system dynamic performance has improved appreciably with the inclusion of incremental dc link power flow as an additional state variable as compared to that obtained when system interconnection is through the ac link only. Another technique used for frequency regulation is battery energy storage facility. Kottic et al. [122] in their work proposed battery energy storage in island power system for better frequency regulation. Their observation reveals that this facility reduces drastically the frequency deviations resulting from sudden demand variations. However they have neglected the generation rate constraints of thermal units while Lu et al. [123] discussed the effect of battery energy storage on a two area reheat thermal system with generation rate constraints. Tsang and Sutanto [124] have studied the application of a battery energy storage system to improve the damping of an electric power system. Performance of the battery energy storage system using proportional integral controller to damp both transient and dynamic oscillation was also presented.

A duplex and distributed communication system seems to be the most suitable solution to meet and ensure good quality of ancillary services. Bhowmik et al. [125] proposed with deregulation of the power generation sector, the necessity for an enhanced and open communication infrastructure to support an increasing variety of ancillary services is apparent. His work focuses on the communication network requirements for the third party load frequency control service. Data communication models are proposed based on queuing theory. Simulation is performed to model the effects of certain type of signal delays on this ancillary service.

2.6 Summary

A comprehensive literature survey about load frequency control problem is presented in this chapter. Various control techniques, such as classical, adaptive, intelligent, and other schemes proposed by research workers like parallel HVDC link to the existing AC tie-line, battery energy storage and establishment of enhanced and open communication infrastructure have been thoroughly discussed.