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Review

Challenges and Opportunities of Load Frequency Control in Conventional, Modern and Future Smart Power Systems: A Comprehensive Review

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Abstract: Power systems are the most complex systems that have been created by men in history. To operate such systems in a stable mode, several control loops are needed. Voltage frequency plays a vital role in power systems which need to be properly controlled. To this end, primary and secondary frequency control loops are used to control the frequency of the voltage in power systems. Secondary frequency control, which is called Load Frequency Control (LFC), is responsible for maintaining the frequency in a desirable level after a disturbance. Likewise, the power exchanges between different control areas are controlled by LFC approaches. In recent decades, many control approaches have been suggested for LFC in power systems. This paper presents a comprehensive literature survey on the topic of LFC. In this survey, the used LFC models for diverse configurations of power systems are firstly investigated and classified for both conventional and future smart power systems. Furthermore, the proposed control strategies for LFC are studied and categorized into different control groups. The paper concludes with highlighting the research gaps and presenting some new research directions in the field of LFC.

Keywords: automatic generation control (AGC); frequency deviation; interconnected power systems; load frequency control (LFC); supplementary frequency control; secondary frequency control; smart grids; tie-lines power deviation

1. Introduction

1.1. An Overview and Motivations

The complexity of power systems is growing due to: (i) increasing the penetration of renewable energy resources; (ii) adopting new concepts such as smart grid; and (iii) digitalization of the power systems control based on unsafe communication systems. The aforementioned reasons directly affect the power systems operation, stability, and security. One of the most important indexes of power systems is the voltage frequency. Recently, frequency control in power systems has gained a considerable attention due to its importance.

Frequency control is usually divided into three control levels, i.e., primary, secondary, and tertiary control levels. Primary frequency control loop is responsible for intercepting the frequency decline before triggering the under/over frequency protection relays. The primary frequency control is usually implemented by the governor droop which results in steady stated errors. The secondary frequency control, which is called load frequency control (LFC) or automatic generation control (AGC), is responsible for regulating the frequency in power systems and has two main goals: (i) maintaining the frequency into a desirable range; and (ii) controlling the interchange power through major tie-lines between the different control areas. The main task of tertiary control level is re-dispatching generating units and ancillary reserve after a sever disturbance.

With increasing the penetration level of renewable resources such as wind farms and photovoltaic plants in power systems, the uncertainties of active power production is highly increased, thus determining frequency variations. Such increase in active power fluctuation, beside the demand stochasticity, the frequency of power system would be highly oscillated. Therefore, future power systems need more robust and optimal LFC approaches that can handle such problems.

Many control approaches have been suggested for LFC in interconnected power systems. These approaches can be categorized into four groups: (i) classical control approaches focus on designing proportional-integral-derivative (PID) controllers for controlling the frequency and tie-lines power flows; (ii) modern control approaches including optimal control method, sliding mode control schemes, and adaptive control systems; (iii) intelligent control schemes, such as fuzzy control systems; and (iv) soft computing-based approaches for controllers' parameter tuning which had a considerable attention from researchers in the last decade.

1.2. Survey Methodology

Several methodologies can be followed for conducting a good and systematical review of the state of the arts [1–7]. In this section, the methodology used for conducting this review of the LFC state of the art is comprehensively described. For conducting this comprehensive review, the most prestigious and well-known databases such as Scopus, IEEE explore, Science Direct, and Springer are searched for articles published in the field of LFC using specific keywords. It is important to mention that we focused only on the online published research such as research articles, review papers, conference papers, scientific books, and standards. In the following, we discuss the methodology used in this paper item by item. The used databases that searched for achieving this review are Scopus, IEEE Explore, Science Direct, Springer, Taylor and Francis, and Wiley publisher. In our search, we used keywords such as "load frequency control", "automatic generation control", and "frequency control". To ensure the quality of this work, only ISI and "Q1, 2" journals were reviewed. Likewise, the IEEE sponsored and co-sponsored conference papers are checked. Table 1 introduces the complete list of keywords used in the search and other information of search methodology.

The first search using the above-mentioned methodology yielded 748 papers, in which 513 papers are remained after removing the duplication. Afterward, the abstracts, contributions and titles of the above selected papers are screened based on the criteria and aim of this paper which resulted in removing 203 papers. The final paper lists are carefully and fully read by our expert team in this on the topic of LFC. In addition, it is worth mentioning that this review paper has passed a comprehensive review process from two expert colleagues in the topic of LFC before being submitted to Energies Journal. Figure 1 shows the flowchart of the review process used for conducting this review paper.

It might be beneficial for researchers to present some statistical analysis on the results of the methodology used in this work. As mentioned above, different types of publications are used in this comprehensive review, as introduced in Table 2. As shown in Table 2, the article journals cover the majority of the reviewed papers, while only 54 conference papers are selected as useful papers.

This paper covers the literature t published from 1953 to 2018. In addition, the cited literature is a collection of 54 years of distinguished research on LFC problem. It should be noticed that the subject of the paper is too general; however, this type of papers can be useful for novices and freshmen to show the route and research tendency over the years. As similar review papers can be found on this subject, "LFC problem", which is published in high ranked journals in previous years. Figure 2 shows the chart of the number of publications over years. As shown in this figure, most of the literature is from the last five years. In addition, the growing trend of the works shows the interest of researchers in these years.

Table 1. Description of the used review methodology.

Issue	Criterion
Sector	Power System (PS)
General Topic	PS operation and control
Discipline	Frequency control
Very specific topic	Load frequency control (LFC)
Keywords I	Load frequency control, automatic generation control, secondary frequency control
Keywords II	LFC, AGC, frequency regulation, supplementary frequency control
Language	English
Availability	Online available
Databases	Scopus, IEEE, Springer, ScienceDirect, Taylor and Francis, and Wiley
Publication type	Research articles, Conference papers, Books, and Standards

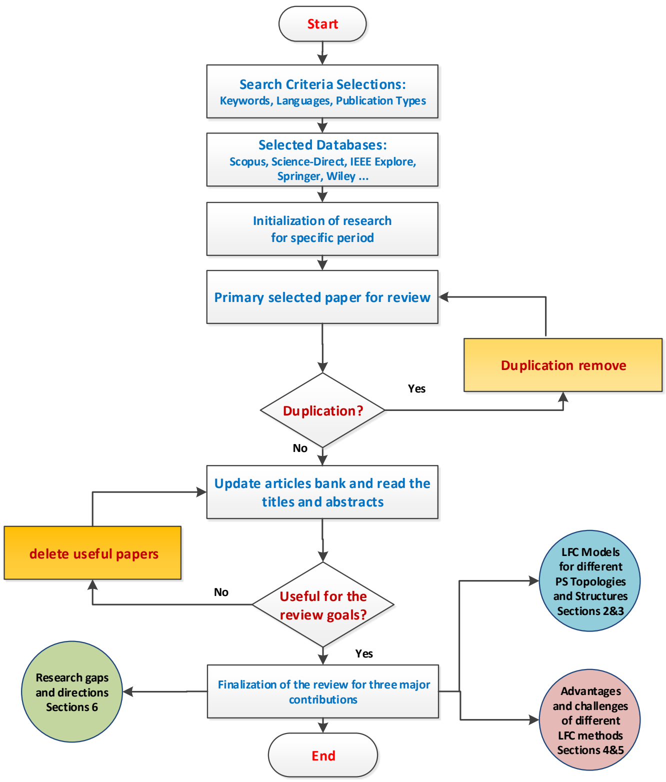


Figure 1. Flowchart of the used review methodology. LFC: load frequency control.

Table 2. Description of the used review methodology.

Issue	Number	Percentage
Articles	256	81.79
Conference papers	54	17.25
Standards	-	-
Books and book chapters	3	0.96

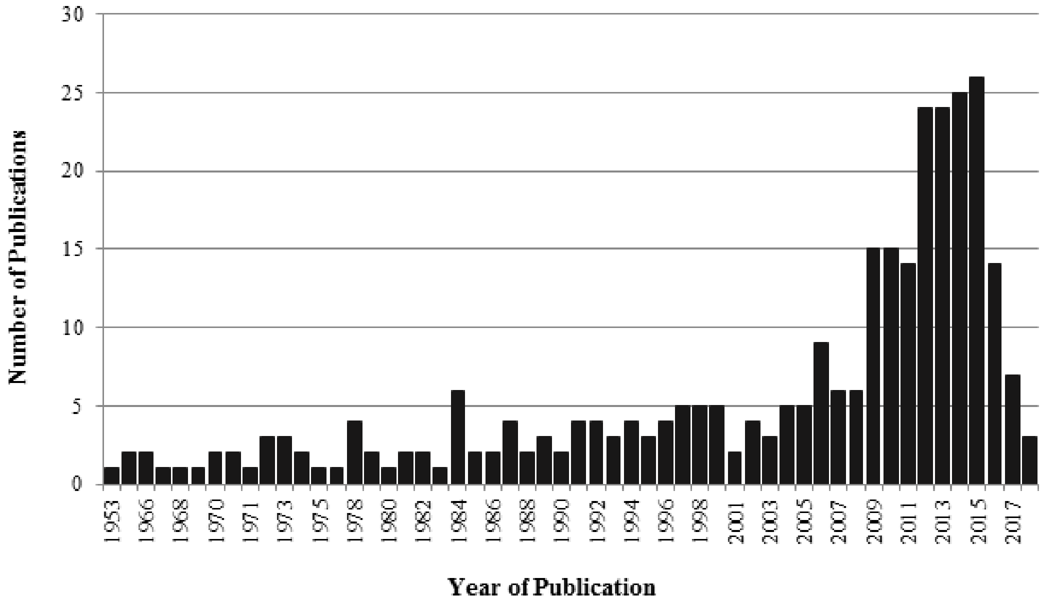


Figure 2. The cited publications over the years.

1.3. Contributions and Review Structure

As final words in this section, the specific topic that this paper covers is briefly introduced. As it is known, power system operation and control is a wide research field of power systems which includes topics related to both frequency and voltage stability and controls. Nowadays, due to reasons mentioned in the Subsection 1.1, frequency control topic has gained considerable attention from researchers. However, this topic covers some very deep and specific topics such as primary frequency control, secondary frequency control, tertiary frequency control, reserve management, power system inertia support methods, and frequency emergency control and protection. Secondary frequency control, called load frequency control, is a very specific topic of frequency control which deals with controlling the frequency due to small disturbances such as load fluctuations and renewable power variations. In this paper, we highlight two important specific points, i.e., models and methods of LFC. Frequency response models are very important for researchers. Therefore, we introduce the most important frequency response models and divide them into two main groups, i.e., model structures (named conventional) and models with emergence technologies. This paper reviews the control methods proposed for LFC in the last decade. In this review, we highlight the advantages and challenges of each control method. Furthermore, a comparison between some methods are clearly presented. Moreover, the research gaps and directions are introduced in this paper which can be a good guideline for the researchers.

This review highlights the suggested control approaches for LFC in power systems. In addition, the frequency response model proposed for conventional power systems is surveyed. Furthermore, LFC models in modern power systems, micro-grids, and future smart grid models of LFC are examined. Likewise, trends and future research directions are also presented. An overview of this paper is depicted in Figure 3. Due to its importance in LFC studies, frequency response modeling of different power system structures is firstly reviewed. In this regard, as shown in Figure 3, LFC models are divided into two main groups, i.e., conventional and future LFC models. The conventional structures of LFC models are surveyed based on their configurations. Consequently, frequency response models of signal control areas, and dual-area, traditional three-area and four-area power systems are comprehensively reviewed. In the literature, many types of system models and configurations have been presented considering different generation types, such as thermal, gas, and hydro power plants. Afterward, configurations of modern and future power system models for frequency studies are divided into five main groups: LFC models with direct current (DC) links and power electronic devices, LFC of power systems under deregulation, LFC of power systems with high penetration of renewable energy resources and distributed generation, LFC models suitable for smart grids, and LFC models in microgrids. The comprehensive reviews in the above-mentioned LFC models are introduced in Sections 2 and 3, respectively. Furthermore, as shown in Figure 3, a taxonomy of different control techniques proposed for LFC, such as classical control approaches, optimal control methods, adaptive and variable structure methods, and robust schemes is also surveyed. In this regard, advantages and challenges of each control approach proposed for LFC are highlighted, which can be found in Section 4. Moreover, A comprehensive survey on soft computing-based control approaches including optimization problems and comparisons is given in Section 5. Figure 3 shows that this paper also highlights some research gaps and new research directions in the topic of LFC introduced in Section 6. Finally, Section 7 concludes.

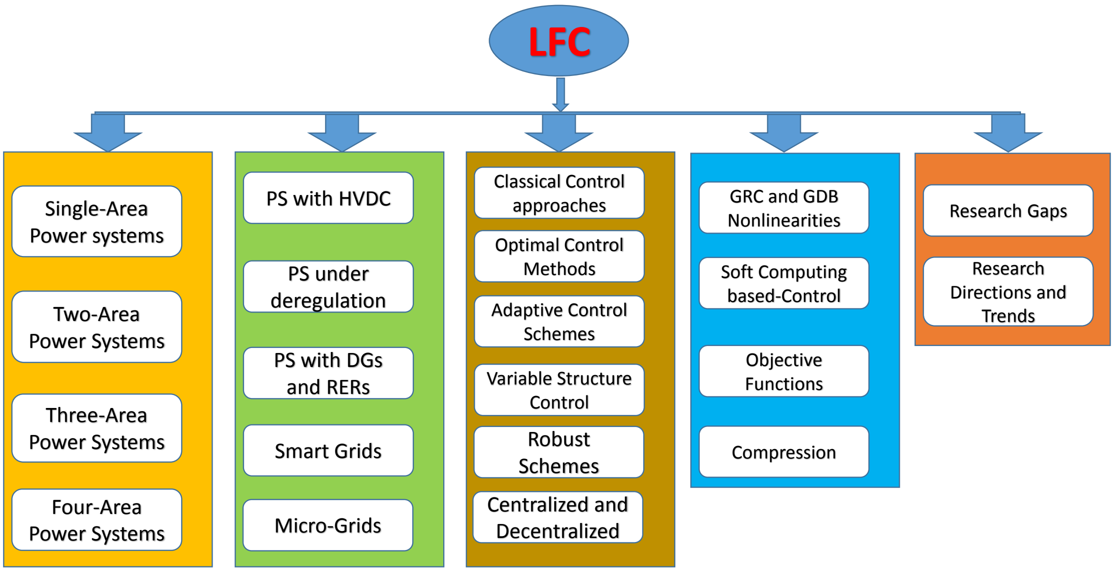


Figure 3. Flow chart of LFC state-of-the-art power systems: conventional, modern and future power systems. PS: power system; GDB: governor dead-band; GRC: generation rate constraint; HVDC: high voltage direct current; DG: distributed generation.

2. Survey on Different Load Frequency Control (LFC) Topologies and Structures

Conventional power systems, in this section, refer to electric power system in which the electricity is generated from fossil energy sources. In reality, thermal units, hydro power plant, and nuclear generating units are the well-known power plants for such systems. Owing to their scale, power systems are usually divided into single-area, two-area, three-area, and four-area power systems. In the literature, several frequency response models are suggested for LFC in which a comprehensive survey regarding power systems models for LFC is given in the following subsections.

2.1. Single-Area Power Systems

First studies on the topic of frequency control relate to design and implement load frequency controllers for single-area power systems. Several single-area power system models incorporating LFC control schemes are investigated in the literature [8–20]. In [8–10], single-area power systems consisting of thermal power plants are marked out. A mathematical dynamic model of frequency response for single-area power systems is discussed in [8,15,16]. Single-area frequency response models for power systems with multi energy sources such as hydro, gas and thermal sources are presented in [18–20]. In [14], a frequency response model of electric power systems consisting of hydro power plants is well-described. An automatic generation control system for hydro power systems considering some nonlinearities is suggested in [15,21]. The interaction between the active and reactive power controls and their impacts on LFC models of single-area power systems are illustrated in [10].

2.2. Dual-Area Power Systems

An overview of LFC and AGC systems in two-area power systems is presented in [22–40]. Tie-lines models and their effects on LFC of two-area power systems are studied in [22,23]. The LFC models for two-area power systems considering the effects of voltage control loops in the frequency response are developed in [24,30]. In [26–28], frequency response models for two-area power systems considering governor dead-band (GDB) and the generation rate constraints (GRC) nonlinearities are suggested. Discussion on the reduction of the frequency response model order to reduce its complexity is presented in [25,39,41]. The LFC models of multi-source two-area power system considering nonlinearities are marked out in [37]. References [31,38,39] deal with LFC models of two-area power systems with parametric and nonparametric uncertainties. LFC scheme for two-area power systems tied together via HVDC/DC transmission links is proposed in [35]. Two-area power system frequency response models consisting of reheat-thermal turbines connected by AC/DC links are presented in [35,42,43]. In [22,23,30,31], load frequency control schemes for thermal–thermal two-area power system taking into account the delay in communication channels are proposed. A frequency model of reheat thermal turbine with governor dead-band zone in two area power systems is marked out in [22–28]. In [34–36], GRC non-linearity is considered for reheat thermal turbine-governor system in two-area power systems. LFC scheme for hydro–hydro interconnected power systems considering the hydro power plants non-linearities is proposed in [38,44,45]. LFC models for two-area power systems considering superconducting magnetic energy storage (SMES) system are proposed in [46,47]. In [48], a frequency control model for two-area power systems considering the contribution of batteries and SMES is described. Reference [49] proposes LFC model of conventional two-area power systems combined with the participation of electric vehicles and energy storage systems. Stochastic nature of electrical load is considered for LFC models in [31,32]. Renewable energy resources uncertainties are taken into account for LFC model in [40]. Discussion on discrete modeling of LFC in two-area power systems is presented in [28].

2.3. Three-Area Power Systems

Studies on LFC modeling for three-area interconnected power systems are presented in [50–60]. A LFC model for three-area interconnected power system in which steam-hydro power plants are considered in the first and second areas while the third area has a steam power plant only is given in [50]. Thermal power system divided into three control areas are studied in [61,62]. Radial and ring connections between the different control areas in three-area interconnected power systems are discussed in [63]. A LFC model for three-area power system considering GDB and GRC nonlinearities is presented in [56–59]. The effects of communication channel delay on LFC in three-area interconnected power systems are investigated in [64]. References [60,62] highlight the impacts of parametric uncertainties on LFC of three-area interconnected power systems. Frequency response model of three-area thermal power systems are proposed in [65,66]. The LFC for three-area hydro power systems is marked out in [59,67–69]. Load frequency controllers are designed for a hydro–thermal power system divided into three-areas [50,70]. The LFC for multi-source power systems in which thermal, gas, and hydro energy sources are considered is proposed in [60].

2.4. Four-Area Power Systems

Large scale power systems are usually divided into several control areas to maintain the frequency in a permissible range. LFC challenges in four-area interconnected power systems are presented in [71–81]. As a first work in this field, a LFC for four-area interconnected hydro power systems is proposed by Malik et al. in [73]. In [71–74], frequency response models of four-area interconnected power systems suitable for LFC are introduced. A LFC model for interconnected power systems with nonlinearities such as GDB and GRC is considered in [79]. The uncertainties of power system parameters are taken into account by using a fuzzy control for a LFC model in [75]. A four-area interconnected power system with different energy sources and turbines such as non-reheat thermal, reheat thermal, gas, and hydro power plants is presented in [77]. Four thermal power-areas are connected together by different connection structures, such as longitudinal and ring connections are considered in [78], in which each area consisting of three thermal units and one hydro unit, is proposed in [80,81]. LFC for three-area consisting of reheat thermal units connected by a tie-line to another hydro control area is presented in [57].

3. Survey on LFC Emerging Technologies and Concepts

The penetration level of renewable energy resources in power systems has been increasing for many reasons. In addition, new concepts such as smart grids, micro-grids, and deregulation have affected the modern power system control and stability. Therefore, many new control approaches are suggested to mitigate the effects of increasing the uncertainties and complexity of future power systems. In this section, frequency response models of modern and future power systems are comprehensively reviewed. Likewise, frequency response models with HVDC transmission links, electric vehicles, demand response and renewable energy resources are well-surveyed.

3.1. Electric Power Systems with HVDC

Due to their numerous technical and economic advantages, HVDC transmission links have been widely used in modern electric power systems. Therefore, HVDC dynamic models have been considered in LFC studies to investigate their impacts [49,82–87]. In this regard, two- and three-area power systems connected together by AC/DC tie-lines are studied in [84–86]. A combination of AC transmission lines and HVDC/DC links is used to tie two control-area power system, which can be viewed in [83,84]. HVDC transmission links between the different control areas in four-area interconnected power system are considered in [82,87], while DC transmission links are used to tie the different control area in five-area power system in [87].

3.2. Electric Power Systems under Deregulation

With moving power systems toward the restructuring concept, new control methods have been proposed for deregulated power systems. LFC modeling problems for deregulated power systems have been addressed in [88–100]. Under deregulation, a power system is divided into different parts so that each part has its own possessor. In this regard, power distribution companies (DISCOs), power transmission companies (TRANSCOs), and power generation companies (GENCOs) are supervised by an independent system operator (ISO) [88–92]. In this new environment, the GENCO may or may not participate in LFC service. Providing ancillary services in deregulated power systems is based on competitive electricity market [92–95]. In the literature, frequency response models are developed for different types of power systems under deregulation [90–97]. Frequency response models suitable for LFC studies in deregulated power systems consisting of thermal units only are suggested in [94–96]. LFC schemes for hydro power systems under deregulation are presented in [101,102]. A multi-source power system frequency response model under deregulation is marked out in [103]. AGC models are proposed for different restructured power systems configurations, i.e., three-area power systems [90,91,98], and four-area power systems [99,100].

3.3. Power Systems with Distributed Generation and Renewable Energy Resources

Due to their features in reducing emission and green house problems, distributed generation (DG) and renewable energy resources (RERs) have gained a considerable attention in the last decade. LFC problems with contribution from DGs and RERs have been solved in [14,104–122]. Power system model for LFC studies considering the participation of flexible alternating current transmission system (FACTS), photovoltaic (PV), and wind turbine generator (WTG) is proposed in [111–122]. LFC challenges of power systems with high contribution from DGs are discussed in [112–117]. The frequency response from doubly fed induction generator driven by a wind turbine is proposed in [118–121]. Frequency response models suitable for power systems with high penetration of renewable energy sources are suggested in [112,113,122].

3.4. Micrograids

LFC models of electric hybrid power system with fuel cell, wind power, and PV are presented in [123–125]. A micro-grid and hybrid system consisting of PV, WTG, micro turbine, fuel cell (FC) and aqua electrolyzer (AE) are considered for modeling the LFC [64,126–134]. The contribution of electric water heater, dynamic demand response, and electric vehicles to LFC of micro-grids is investigated in [135–137]. Non-linear microgrid models for LFC studies are also suggested in [130,131].

3.5. Smart Grids

Recently, smart grid control topics have gained considerable attentions from researchers due to its great advantages. Several new LFC schemes for future smart grids system have been developed in [128,138–148]. LFC models considering the contribution of electric vehicles (EVs) are presented in [141]. Likewise, a coordination model between electric vehicles and heat pump water heaters is suggested for LFC in future smart grids [142]. Dynamic demand response which is considered as a key feature of smart grids has been developed for LFC in [138,139,149]. In [128,138–143], frequency response models considering the contribution of different storage types have been proposed and evaluated. A new frequency response model of plug-in EVs is proposed for primary and secondary frequency control levels in [150]. The problems of possible cyber-attacks to LFC systems in future smart grids are discussed in [144,145].

4. Taxonomy of Control Technique

In the past, various LFC strategies were designed for power systems. Control techniques can be classified into different categories: classical control approaches, variable structure and adaptive control schemes, robust control methods, digital control and intelligent techniques. In this section, a completed survey on the suggested control methods for LFC in power systems is presented. The classical control approaches are firstly reviewed in Section 4.1. Then, the application of optimal control methods to LFC in power systems is marked out in Section 4.2. Likewise, the suggested adaptive control methods for LFC are reviewed in Section 4.3. Furthermore, variable structure control scheme applications to LFC in different types of power systems are highlighted in Section 4.4. Moreover, the different robust control approaches are reviewed for LFC in Section 4.5. Finally, Section 4.6 reviews the different centralized and decentralized control schemes proposed for LFC in power systems.

4.1. Classical Control Methods

Conventional control approaches are based on classical controllers usually applied to the governor to minimize the area control error (ACE) in power systems to enhance the frequency response. In the past, several classical control methods have been proposed for LFC in power systems [67,68,72,81,151–186]. Gain and phase margin analysis are used in classical control procedure using Nyquist and Bode techniques [151–153]. The proposed method in [154] controls frequency deviation due to load variation by related area control center in which no interaction between frequency and tie-line power is considered. In order to regulate the frequency and tie-line power flow using communication links, decentralized proportional-integral control [162], dual mode proportional–integral (PI) controller [157] and PI control for hydropower system [158] have been proposed. The coordinated system-based technique for correcting the time error and unintentional interchange is presented for AGC in [187,188]. The small signal analysis for a hybrid system is used to design a PI controller in [165]. PI control for micro source systems is presented in [156]. PI and a model predictive control approaches are applied to attain best closed loop performance [160]. Integral derivative (ID) controller for LFC is presented in [163,164]. Unified PID tuning method [81] and optimal Multiple Input–Multiple output (MIMO-PID) control is used for LFC [167]. Chaotic optimization algorithm is used for determining the parameters of PID controller in multi-area load frequency control in [168]. Different optimization methods are used in [171–174] for tuning the PID controllers' parameters of LFC. Authors in [183] presented the performances of different classical control approaches, e.g., proportional–integral (PI), integral plus double derivative (IDD), integral (I), and proportional–integral–derivative (PID), which are compared with recently introduced Proportional–Integral plus Double Derivative (PIDD) controllers for AGC [34].

Advantages and Drawbacks: The classical control approaches are well-investigated for LFC in power systems and in reality, there are several electric power systems using these approaches for LFC. However, there are several drawbacks and problems that need to be handled for future power systems. The main problems and drawbacks are as follows:

- The problem of optimally tuning the parameters of load frequency controllers needs more realistic methods.
- The robustness against parametric and nonparametric uncertainties need to be clearly-solved.
- These control approach should be developed to have tolerance against sensor and actuator faults.
- They need more investigation for their robustness against possible cyber-attack issues.

4.2. Optimal Control Methods

The optimal control methods have provided solutions for multi-variable control systems. These kind of methods consider state variable model and the minimization of an objective function. Hence, optimal control methods are feasible if all state variables are available to design the feedback control signals. If the system state vector is observable with some measurements of the control-area, this requirement can be met. This requirements make optimal control method complicated and undesirable for large-scale power system. In [189], a new feedback control law for two-area interconnected power systems with non-reheat thermal power plants is designed using the regulator problem of optimal control method and a state space variable model. In last decade, modern optimal control theory is used for designing load frequency controller that can optimally control both frequency and tie-line power deviations. Some LFC schemes based on modern optimal control theory are presented in [190–196]. In [197], optimal linear regulator theory is used to design a linear regulator for load frequency control in power systems. A plant response time is designed using linear optimal control theory and its effect on the closed loop poles is investigated in [198]. A more realistic LFC model is developed in [24] under different load conditions by considering the excitation system for voltage regulation and optimal responses. In [199], a survey of optimal linear regulator theory and its application for LFC is presented. The prescribed requirements of optimal control theory makes this theory unrealistic in some cases, but with the developments in the dynamic state estimation methods, the unavailable states can be obtained by well-designed observers. Many state estimation construction methods have been introduced in [190–195]. State estimator with decaying error using a nonlinear transformation based on optimal observer for AGC schemes is presented in [194]. A distributed dynamic observer is locally applied in [193] to reduce the order of the model of the full order state observer. An observer for nonlinear systems is also presented in [200]. Due to the complexity and practical limitations of LFC in multi-area system, a suboptimal control strategy is investigated in [201–203]. To realize the decoupling of the interconnection into its subsystem components, model and singular perturbation techniques are employed [204]. Suboptimal and near-optimal controls are presented in [201] and a suboptimal AGC regulator scheme for a two-area interconnected system in [205,206]. Local controllers are employed for each subsystem to achieve decentralized controllers using local information to generate local control inputs by locating the closed loop poles of each controller in specified places on the complex plane. Lyapunov's second scheme applying minimum setting time theory is also introduced in [207] for AGC regulator design.

Advantages and Drawbacks: Optimal control methods have several advantages such as optimally controlling the systems and regulating all the dynamic states of the controlled systems. These methods can play an important role in the future power systems if some drawbacks, given below, are well-addressed.

- The dynamic states of the power system need to be observed in real time.
- Cyber-attacks issues need to be considered in the designed dynamic estimators.
- The parametric uncertainties in the designed observers need to be considered.
- Dynamic observers that can eliminate the unknown input effects need to be developed.

4.3. Adaptive Schemes

The performance of frequency controller may not be optimal if the operation point of the system changes. Hence, it would be preferable to update the parameters based on the operating point for achieving a better control performance. Generally, adaptive control schemes can be classified into self-tuning control (STC) schemes and model reference control schemes. The under control process is thus less sensitive to the parameters and the dynamics which is not considered by using this approach. Different adaptive control schemes [9,208–213] have been proposed for LFC in interconnected power systems. STC approaches were presented for LFC in power systems by some authors [192,214–217]. The adaptive control criteria and the practical difficulties found in LFC to achieve this criterion are presented in [209]. In [208], the implementation of an adaptive control scheme on the Hungarian power system was described. An adaptive controller with proportional integral control technique to confirm the hyper-stability conditions is presented in [9] for considering the changes of plant parameters. The implementation of an adaptive control scheme on a microprocessor for LFC is investigated in [210]. A self-tuning regulator for LFC considering the interaction between voltage and frequency control loops is presented in [218]. A reduced order adaptive controller for LFC is suggested in [212] and a multi-area adaptive load frequency control strategy is developed in [211]. Some other issues of a hydro–thermal systems are described in [213,219,220]. In [214], a self-tuning method for the load frequency control problem of interconnected power systems is presented. LFC based on adaptive fuzzy approach is presented nto achieve better performance for several operating points [221]. A self-tuning approach is presented in [46] to improve the performance of AGC as a stabilizer for main AGC loop and SMES. A self-tuning controller to minimize a multi variable optimization function including cost function and constraints on control effort is discussed in [213]. A new adaptive LFC considering uncertainties of parameters is proposed in [12] with a combination of robust control, the Riccati equation and adaptive control. Investigation of load frequency control for a two-area hydro–thermal system by using Adaptive Neuro-Fuzzy Interference System (ANFIS) is presented in [222]. An adaptive fuzzy gain scheduling scheme for proportional integral and optimal LFC is described in [219]. An application of knowledge-based adaptive governor control is presented in [111]. To improve the performance of power system frequency controllers, a self-tuning steam turbine control strategy proposed in [111].

Advantages and Drawbacks: Despite the remarkable advantages of these control schemes, adaptive controllers are complicated, need a perfect model following condition, and on-line model or explicit parameters identification. Therefore, these methods are sometimes unrealistic and difficult for implementation.

4.4. Variable Structure Control Methods

The variable structure controllers exhibit improved dynamic performances in the case of problems such as uncertainties of systems parameters. In addition, variable structure control schemes determine the appropriate parameters of the controller that led to effective enhancement of transient responses under load disturbances in the power systems. Authors in [184,185] proposed a control method for LFC in power systems by using a variable structure control scheme. Regarding to variable structure theory and optimal linear control, in [223] a LFC method for interconnected two-are hydro–thermal systems was proposed. In addition, a variable structure control method for a multi-area interconnected system with considering the non-linearities such as governor dead-band and generation rate constraint is proposed in [79]. In [78], a decentralized approach based on structured singular values is proposed for load frequency control.

Advantages and Drawbacks: Variable control structure is a type of adaptive control schemes. It has many implementations in industrial. However, its applications to power systems need more investigations since it is not implemented for LFC in reality. The well-known drawbacks of these control methods are given below:

- The performance of variable structure control methods for power systems with a high penetration level of highly variable sources such as renewable energy resources need to be investigated.
- This control is not optimally tuned in the above studies.

4.5. Robust Schemes

Load frequency control methods encounter problems of uncertainties and changes in system parameters and characteristics. In addition, the operating points load scenarios vary mostly over a wide range during operation. Thus, the robust control design approach is used to provide better performance (robustness) to deal with changes of the system parameters. The controllers in robust scheme approaches are designed for the scope of robust stability and performance and not only for satisfying nominal stability and performance for the load frequency problem. A robust control scheme is proposed in [224,225] based on the Riccati equation for a single area thermal power system. In [11], the requirements to design the robust load frequency controller based on Riccati equation as bounds of the system parameters are found. The proposed robust controller is effective, simple and guarantees the stability of the overall system for all possible uncertainties. In [226], a decentralized LFC using Riccati equation for three-area power system with parametric uncertainties is proposed. A new robust adaptive control scheme is proposed in [12] with a combination of the robust control method and adaptive control scheme approach for the problem of LFC in power systems. Combining the robust control scheme with adaptive control methodology, the robust control method is used to cope with small uncertainties of parameters and adaptive control methodology for large uncertainties of parameter. In [227], analysis and heuristic design guidelines of LFC based on quantitative feedback theory is suggested to offer an orderly methodology for control system synthesis. In addition, a robust load frequency control scheme based on the control approach is presented in [228] considering uncertainties of parameter. In the same way, a robust control scheme for the load frequency control problem is proposed in [229] to improve robustness against uncertainties based on a control method using Linear Matrix Inequalities (LMI) technique. A robust stabilizing control method based on the Riccati equation is proposed in [224] by combining the Lyapunov stability theory, and matching conditions and considering uncertainties. The inter-area damping coefficient is quite improved via using flexible ac transmission systems (FACTS) devices is demonstrated in [230] and a decentralized damping control method based on the mixed-sensitivity reformulation in linear matrix inequality framework is presented. The Q-parameterization theory is used to design a robust controller to control the frequency deviations in [231] which led to a stable control. By locating closed loop poles in a predetermined region to obtain the required transient response and result lower controller order in comparison with the order of comparable robust controllers, such as, LQG and u-analysis is obtained.

Some authors [11,12,227,232–234] proposed a centralized scheme with high order of controllers and led to unfeasibility of these methods for large power system. In addition, decentralization of control to individual areas is important in dynamical operation of power systems. Reduction of the complexity of controllers in order to improve the capability of implementation of these methods is the main objective of decentralized methods. Consequently, the decentralized robust control scheme is suggested for the load frequency control problems of multi-area large power systems. A decentralized robust load frequency controller is suggested in [226] based on the Riccati equation approach embedding the local power system parametric bounds in it to obtain robustness of the controller. Based on the mixed control technique, a new decentralized robust control scheme is proposed in [89,91] for load frequency problem in a deregulated three-area power system. A robust decentralized frequency stabilizer design for static synchronous series compensators was proposed in [235] which considers the uncertainties of a three-area interconnected power system. Analysis and design of a robust load frequency control scheme is discussed in [236]. A decentralized load frequency controller is proposed in [237] based on the optimal control which incorporated an observer. A design guideline of a decentralized robust LFC method is described in [238] based on u-synthesis in multi-area power systems where the information about the controllers design in the previous step is considered in the synthesis procedure, at each step. The linear mixed inequalities for LFC problem is proposed in [66] by considering communication delays. A robust decentralized proportional integral controller design based on the control technique using the linear mixed inequalities with communication delays is proposed in [162] for three-area interconnected power systems. The robust analysis for decentralized LFC for multi-area power system is described in [239] where a robustness analysis against variation of the structure and magnitude variation in the tie-line power flow network is proposed. Tie-line and local modes robustness analysis are completely investigated by using structured singular value and eigenvalue methods, which are presented in [239]. The proposed method is applied to a four-area power system. A decentralized robust control scheme is proposed in [60] based on active disturbance rejection control technique.

Advantages and Drawbacks: Robust control methods are effective controllers that can handle parametric uncertainties. However, These methods have several drawbacks regarding their applications to frequency control in power systems.

- They need a good knowledge of the system dynamic models which is not available in most power systems.
- They are usually designed for a band of uncertainties that is highly variable.
- Their applicability for power systems under some critical conditions such as cyber-attacks and unknown inputs are not investigated.

4.6. Centralized and Decentralized Control Methods

The wide area control scheme is based on the centralized control strategy to cope with the load frequency control problem in which the static and dynamic states of the power system are needed to construct the control signal. The centralized control scheme is based on classes of disturbances of the system [154,202]. The design of centralized and decentralized robust output feedback control methods is proposed in [240] based on mixed theory with pole-placement. A feedback and loop gain is used in [153] to offset the disturbances. A state variable model and the state regulator issue of optimal control theory is used in [189] to develop a new feedback control law. Regarding to large power systems, the decentralized control method is simple and applicable since it reduces the computational burden and communication elaboration. In the concept of the decentralized control method, the complex wide power system has to be divided into some subsystems where every subsystem has its own controller. The decentralized control approach is used for continuous and discrete tie system models in [78,241–250]. By using modeling error compensation technique, the design of decentralized LFC method for power system consisting of two-area with a thermal generation, starting with stochastic state and output models is proposed in [251,252]. A decentralized controller for the load frequency control problem is presented in [70,241,242,246,253] using tunable regulator. To address the load frequency control problem of multi-area power systems with constant disturbances, a class of minimum order robust decentralized controllers is presented in [50]. A new decentralized load frequency control scheme is proposed in [254] by using the governor and voltage controls via a new approach based on Siljak's theory for two-area thermal power systems. A 119th order model is used in [50] to present a decentralized LFC for a three-area power system with nine synchronous machines. A feasible LMI design is investigated in [255] for the effective construction of the control set under state feedback. A decentralized power system load frequency control method exceeding the diagonal dominance limit is described in [243,246,256]. The modeling of a decentralized LFC based on the conventional and intelligent control approach using a fuzzy approach is presented in [162,254,257–260]. The design procedure of a new optimal decentralized load frequency controller is presented in [247]. In addition, the design of the robust decentralized control scheme is discussed in [62,71,81,239,244,261–264] with linear matrix inequalities and iterative technique. The design of a decentralized load frequency controller for a four-area interconnected longitudinal system is presented in [265]. A new optimal decentralized load frequency control method is proposed in [247] for multi-area interconnected power systems. The design of a simple and computationally efficient decentralized load frequency method is introduced in [246] for interconnected power systems based on a reduced-order observer and a PI controller in each area of the power system, which ensures zero static change in area-frequency and tie-line power. A new robust decentralized load frequency controller based on the Riccati-equation is proposed in [226] for multi-area power systems considering the uncertainties of parameters. A decentralized LFC based on structured singular values was proposed in [78]. The multivariable quantitative feedback theory is used in [266] for a load frequency controller in multi-area power systems with system parametric uncertainties. These uncertainties are achieved by simultaneously changing parameters by 40% from their nominal values. A decentralized LFC method based on a multi-objective evolutionary algorithm with AC-DC parallel tie-line for interconnected two-area power system is proposed in [267]. The GA-based decentralized load frequency controller is proposed in [268] for an interconnected two-area power system with redox flow battery considering a thyristor controlled phase shifter in the tie-line. An internal model control method with two-degree-of-freedom is used in [99] to tune decentralized PID controller of the load frequency control in four-area power system. In addition, the two-degree-of-freedom internal model control method for tuning the PID controller is discussed in [81,269] for load frequency control in conventional environments. A decentralized load frequency control method for interconnected three-area power system is presented in [270].

Advantages and Drawbacks: It is proven that decentralized control approaches are much better than centralized ones. Despite their advantages, decentralized control methods applied to LFC have some problems:

- All the above-mentioned studies present quasi-decentralized control approaches because the total power flow deviation through the tie-lines connected with other areas is requested for constructing the control signal. Since this measured signal is not locally measured, the proposed methods are not fully decentralized ones. However, it is a good research point to develop fully decentralized control approaches for LFC in power systems to improve the power system stability and security.
- It is important to consider cyber-attack issues in the future power system LFC.
- It is of great importance for future smart grids to design decentralized LFC based on wide-area measurement and control systems (WAMCS).

5. Soft Computing Based Control Schemes

5.1. Soft Computing Based Control Schemes

In last decade, evolutionary computing based-control system design has gained considerable attention from researchers around the world due to its advantages. Low solution costs, guarantee of a solution, and its practicability are the well-known advantages of soft computing methods. They can handle technical issues such as uncertainties, nonlinearities, and complexity. In contrast to other methods, the practicability of control methods based on soft computing technique has been verified by several studies. In order to achieve good control and dynamic system performances, soft computing techniques have been used for optimizing the load frequency controllers' parameters. For instance, different evolutionary optimization algorithms have been used to optimally tune the controllers' gains. As a first work in this topic, genetic algorithm (GA) has been proposed as a promising technique for solving LFC problem and other power system problems in [271]. In [110], GA has been also suggested for AGC in hydro–thermal power systems. Likewise, GA is used for tuning the controllers as well as for fuzzy controllers gains for LFC in power systems.

Particle swarm optimization (PSO) is based on population and inspired by the friendly behavior of fish schooling or bird flocking, which is considered as a powerful optimization technique, has been widely used for solving LFC problem in interconnected power systems. In [272,273], LFC problem in single-area power systems is solved by PSO. Likewise, LFC problem in interconnected power systems with multiple sources such as thermal, hydro, and gas turbines has been handled by PSO in [274]. Furthermore, hybrid PSO techniques with other soft computing techniques are proposed for LFC in [275].

Recently, several newly proposed soft computing algorithms have been developed for LFC problem in both conventional and modern power systems. For instance, differential evolution (DE) algorithm [170,276–279], firefly algorithm (FA) [173,280,281], bacterial foraging optimization (BFO) [282,283], artificial bee colony (ABC) [174,284], bat inspired algorithm (BIA) [285–287], quasi oppositional (QO) [54], quasi-oppositional harmony search (QOHS) algorithm [288,289], teaching-learning-based optimization (TLBO) [290], cuckoo search (CS) algorithm [291,292], seeker optimization algorithm (SOA) [293], hybrid Local Unimodal Sampling and Teaching Learning Based Optimization (LUSTLBO) algorithm [178], grey Wolf Optimizer algorithm [294], and wind driven optimization algorithm [295] have been applied to LFC in interconnected power systems. Other evolutionary computing algorithms applied to LFC can be found in Table 3.

Table 3. Comparison between resent studies on LFC/AGC topics in the literature.

Reference No.	System Type Trad./Dereg.	Number of Areas	Generation Source Type	Area Type Multi/Single Source	Other Used Devices	Controllers Type	Optimization Technique
[170]	*Traditional*	2	Thermal	*No*	-	2-DOF PID	DE
[45]	*Deregulated*	2	Hydro–Thermal	*Yes*	DFIGs	FLC	Fuzzy
[296]	*Traditional*	2	Hydro–Thermal–Gas	*Yes*	TCSC	I	IPSO
[103]	*Deregulated*	2	Hydro–Thermal–Gas	*Yes*	-	OOFC	-
[297]	*Traditional*	2	Hydro–Thermal–Wind–Diesel	*Yes*	-	PIDD	TLBO
[298]	*Deregulated*	2	Thermal–Gas	*Yes*	-	I,PI,ID,PID	DE
[101]	*Deregulated*	4	Thermal	*Yes*	-	Fuzzy PID	FA
[299]	*Deregulated*	2	Thermal	*Yes*	TCPS	I	-
[300]	*Traditional*	2	Thermal–Hydro–Gas	*Yes*	TCPS, TCSC	I	IPSO
[301]	*Deregulated*	2, 3	Hydro–Thermal	*Yes*	-	PID	ICA
[302]	*Traditional*	4	Hydro–Thermal	*Yes*	-	DMPC	DMPC
[289]	*Deregulated*	1, 5	Thermal–Hydro–Gas	*Yes*	-	PID	QOHS
[303]	*Traditional*	2	Thermal–Hydro–Gas	*Yes*	TCSC	FOPID	IPSO
[304]	*Deregulated*	3	Thermal	*Yes*	-	DMPC	DMPC
[305]	*both*	2	Thermal–Gas–Hydro	*Yes*	-	FOFPID	BFOA
[306]	*Deregulated*	2	Hydro–Thermal	*Yes*	SMES + TCPS	ANFISC	ANFIS-PS
[307]	*Traditional*	2	Thermal	*No*	SMES	PID	PSA
[308]	*Traditional*	1	Thermal	*No*	SMES	CHB-I	-
[309]	*Traditional*	2	Thermal	*No*	SMES	I	CSA
[310]	*Deregulated*	2	Thermal	*Yes*	IPFC + RFB	I + FLC	BFO
[311]	*Deregulated*	2	Thermal–Hydro–Gas	*Yes*	RFB	I	OHS
[312]	*Traditional*	2	Thermal–Hydro–Gas	*Yes*	RFB	FOFPID	ICA
[313]	*Traditional*	2	Thermal—Hydro–Diesels	*Yes*	TCPS + CES	I	CRPSO
[314]	*Traditional*	*SMIB*	Thermal–Hydro	*Yes*	CES	I	CRPSO
[315]	*Deregulated*	2	Thermal–Hydro	*Yes*	SSSC + CES	I	ICA
[316]	*Traditional*	2	Isolated-wind–diesel–IHPS	*Yes*	CES	SFFLC + PID	QOHS
[317]	*Deregulated*	2	Thermal–Hydro–Gas	*Yes*	CES + TCPS	PI	PSO-SCA

5.2. Objective Functions and Optimization Formulation

Load frequency controllers in interconnected power systems should perform two main objectives when the system is facing a disturbance: (i) return the steady sate frequency back to zero; and (ii) maintain the transferred power at the scheduled values. To achieve these goals, load frequency controllers should be optimally tuned. To this end, several objective functions can be used for formulating the optimization problem of LFC in interconnected power systems. The main goal in LFC is to mitigate the frequency and tie-lines power flow deviations which results in improving the power system operation, control and stability [295]. To mitigate the deviation, area control error (ACE_i) is usually used as an index as follows:

$$\begin{aligned} ACE_i &= \Delta P_i + \beta_i \Delta f_i \\ \text{where } \beta_i &= D_i + \frac{1}{R_i} \end{aligned} \tag{1}$$

where Δf_i is the frequency deviation in p.u., ΔP_i is the power flow deviation in p.u., β_i is the frequency bias, R_i is the governor droop, and D_i is the power system damping.

In addition, other indices such as settling time, overshoot, and oscillation damping improvement can be used in the designed objective function to achieve the goals of LFC decision maker.

Before using soft computing techniques to achieve the best LFC performance, a suitable objective function should be properly used. In the literature, different criteria have been introduced to include the frequency error and tie-lines power in the objective functions. Integral of absolute error (IAE) [162,318], integral of time multiplied by absolute error (ITAE) [319], integral of squared error (ISE) [102,320] and integral of time multiplied by squared error (ITSE) [170,295,321] are the most important criteria used for designing load frequency controllers. The common objective functions used in literatures based on the mentioned criteria for tuning load frequency controllers are as follows [102,295]:

$$J_1 = IAE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left(\alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right) \times dt \tag{2}$$

$$J_2 = ISE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left(\alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right)^2 \times dt \tag{3}$$

$$J_3 = ITAE = \sum_{i=1}^{NA} \int_0^{t_{sim}} \left(\alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right) \times t \times dt \tag{4}$$

$$J_4 = ITSE = \sum_{i=1}^{NA} \left(\alpha_i \left| \Delta f_i(t) \right| + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \left| \Delta P_{tie_{i-j}}(t) \right| \right)^2 \times t \times dt \tag{5}$$

The weights for frequency error in each area (α_i) and transferred power error in each tie-line (α_{ij}) are considered. In the object functions, once the frequency deviation and/or transferred power deviation in some areas and/or tie-lines are more important than others, the appropriate weights are used [295].

Recently, the objective function given in Equation (6) considering the damping of the frequency oscillations and the settling time of both frequency error and tie-lines error, such that the power balance is attained as soon as possible, is proposed for LFC [318].

$$
\begin{aligned}
J_5 = {} & \omega_1 \sum_{i=1}^{NA} \int_0^{t_{sim}} \left(\alpha_i \Delta f_i(t) + \sum_{\substack{j=1 \\ j \neq i}}^{NA} \alpha_{ij} \Delta P_{tie_{i-j}}(t) \right) \times t \times dt + \omega_2 \frac{1}{\min\left(\{(1-\zeta_i),\, i = 1 \ldots n\}\right)} \\
& + \omega_3 \left(\sum_{i=1}^{NA} \left(ST(\Delta f_i(t)) + \sum_{\substack{j=1 \\ j \neq i}}^{NA} ST(\Delta P_{tie_{i-j}}(t)) \right) \right)
\end{aligned}
\tag{6}
$$

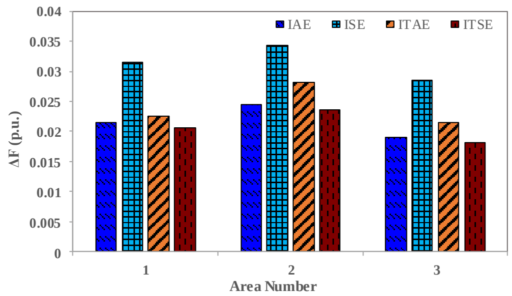
Settling time (ST) can be defined as the time at which the final value of the signal settles to less than 0.00001 [318]. The weight (ω) of each term of objective function should be such that the importance of each term is considered in the aggregate objective function [295].

5.3. Comparison

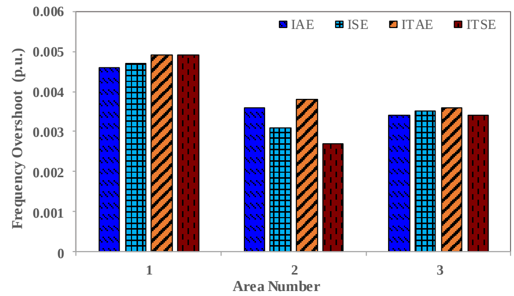
To assess the impact of different criteria used to form objective functions on the optimal solutions of the LFC problem, in this section, the performance of the controllers tuned by objective functions formed based on IAE, ISE, ITAE, and ITSE are compared. Here, PID with filter (PIDF) controllers are used for secondary frequency control. The parameters of PIDF controllers of different areas obtained via wind driven optimization (WDO) algorithm using the mentioned objective functions are given in Table 4. In this section, a 0.01 p.u step increase in the demand of all areas is considered as a disturbance [295]. In this case, the frequency nadir (maximum frequency deviation), frequency overshoot in each area, and the settling time of the frequency signal in each area are presented in Table 5. For further investigation, the maximum deviation and the settling time of tie-lines active power are also given in Table 5. In this table, it can be seen that the IAE and ISE decrease the maximum overshoot more than ITAE. In addition, the results given in Table 5 prove that ITAE decreases the settling time more than IAE and ISE. The settling times, overshoots, and deviations of frequency signals of different areas are depicted in Figure 4. More information about this comparison can be found in [295].

Table 4. The controllers' gains tuned by different objective functions [295].

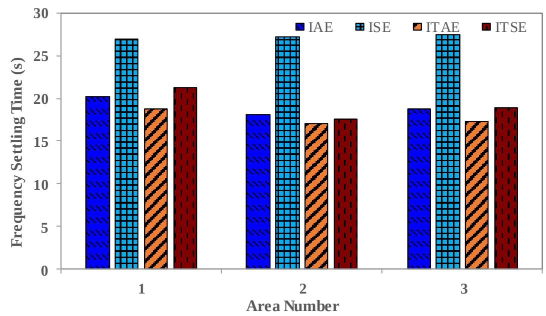
Controller	Parameters	ISE	IAE	ITSE	ITAE
I	Kp	1.11756	−0.6620	−1.0433	−1.0073
I	Ki	−0.37987	−2	−2	−1.5207
I	Kd	−0.23455	−1.1824	−1.1538	−1.2774
I	N	221.73313	127.20	279.6893	300
II	Kp	−1.87535	−2	−1.85951	−0.71544
II	Ki	−0.85221	−1.8080	−2	−1.869451
II	Kd	2	−0.3039	−0.43109	−0.097959
II	N	1	11.8381	199.292	99.57012
III	Kp	−2	−2	−2	−1.95772
III	Ki	−1.84575	−1.800	−1.9165	−1.67929
III	Kd	−1.46660	−1.4519	−1.51080	−1.62555
III	N	209.546920	130.8763	291.22717	148.485



(**a**)



(**b**)



(**c**)

Figure 4. Comparison between different objective functions, i.e., IAE, ISE, ITAE, and ITSE: (**a**) frequency deviations in different control areas; (**b**) frequency overshoot; and (**c**) frequency settling time. IAE: Integral of absolute error; ISE: integral of squared error; ITAE: integral of time multiplied by absolute error; ITSE: integral of time multiplied by squared error [295].

Table 5. Settling times, maximum deviations, and overshoots of both voltage frequency and tie-lines' power flow in case of using different objective functions [295].

Index	Symbol	IAE	ISE	ITAE	ITSE
Settling time (s)	ΔF_1	20.1700	27	18.6900	21.2600
Settling time (s)	ΔF_2	18.1400	27.2400	17.0300	17.5500
Settling time (s)	ΔF_3	18.7700	27.4100	17.3500	18.9300
Settling time (s)	ΔP_{12}	12.9800	28.8100	12.2200	14.8200
Settling time (s)	ΔP_{13}	10.8700	21.0500	9.7600	7.5500
Settling time (s)	ΔP_{23}	8.6700	19.7700	7.5200	7.7800
Maximum deviation (p.u)	ΔF_1	0.0215	0.0316	0.0225	0.0206
Maximum deviation (p.u)	ΔF_2	0.0245	0.0344	0.0282	0.0236
Maximum deviation (p.u)	ΔF_3	0.0191	0.0285	0.0215	0.0182
Maximum deviation (p.u)	ΔP_{12}	0.0044	0.0211	0.0039	0.0035
Maximum deviation (p.u)	ΔP_{13}	0.0025	0.0047	0.0052	0.0024
Maximum deviation (p.u)	ΔP_{23}	0.0012	0.0011	0.0016	9.5292×10^{-4}
Maximum overshoot (p.u)	ΔF_1	0.0046	0.0047	0.0049	0.0049
Maximum overshoot (p.u)	ΔF_2	0.0036	0.0031	0.0038	0.0027
Maximum overshoot (p.u)	ΔF_3	0.0034	0.0035	0.0036	0.0034
Maximum overshoot (p.u)	ΔP_{12}	0.0026	0.0029	0.0031	0.0018
Maximum overshoot (p.u)	ΔP_{13}	0.0032	0.0038	0.0043	0.0023
Maximum overshoot (p.u)	ΔP_{23}	0.0015	0.0019	0.0023	0.0013

Comparison between the recent studies on LFC/AGC taking into account system type, control-areas number, generation type, integrated devices to power system, controller structures, and the used optimization method is given in Table 3. It is clear that the recent studies focus on LFC in power system under deregulation. In addition, due to the increasing penetration level of renewable energy resource in modern power systems, recent studies focused on the contribution of energy storage systems to power system.

6. Research Gaps and Directions

The face of power system is changing due to many reasons, such as environmental concerns, fossil fuel problems, energy system security, economical and operation cost issues. Many countries around the world have decided to increase the penetration level of renewable energy resources such as wind and solar energy resources in their energy system. Increasing the share of RERs in power systems results in many problems such as reducing the total inertia of the system, increasing the power imbalance in the short-term operation of power systems, and increasing the frequency and tie-line power oscillations. Reducing the total inertia causes many problems to ISO such as increasing the frequency nadir (maximum frequency deviation) and making the system oscillatory. On the other hand, increasing the power imbalance in the short-term operation results directly in increasing the frequency oscillations. It is clear that modern and future power systems would experience problems in frequency control. These systems would encounter a lack in the system inertia and suitable damping. Therefore, suitable control methods and ancillary services such as primary and secondary reserves are needed for online controlling such frequency problems. Based on the literature survey, some research gaps in the topic of LFC which need further studies are listed below:

- Increasing the robustness of control methods applied to LFC
- Proposing optimal-robust control methods for LFC can handle both of the parameter and power production variations
- Proposing new objective functions for LFC that can improve the power system performance
- Investigating the reliability of LFC loops
- Increasing the ability of LFC system to handle cyber-attack issues
- Proposing suitable control methods that can detect and isolate sensor faults in LFC loops
- New fault diagnosis methods suitable for LFC are needed
- Designing control methods for power systems modeled without assumptions
- Considering the interactions between LFC and other control loops such as LFC and AVR control loops
- Proposing new control methods make use of WAMS

Nowadays, there are great activities in investigating the ability of demand-side participation in providing some ancillary services for ISO such as primary and secondary reserves, and LFC services. Therefore, realistic participation approaches are needed that can increase the oscillation growth in frequency. As a good research direction for researcher, a suitable coordination between the demand-side and generation-side participation in LFC can be proposed for modern power systems. Likewise, the infrastructures of modern power systems need more investigations to provide demand-side participate in LFC. Electric vehicles as well as other intelligent loads in the demand-side can contribute to LFC where many investigations regarding infrastructure and ancillary service market are needed.

7. Conclusions

In this paper, a state of the art on load frequency control in power systems is presented. Due to their importance, frequency response mathematical models of different power system types such as conventional and smart systems are completely reviewed. In addition, different types of smart system models such as modern power systems with high penetration of renewable energy resources distributed generation, micro-grids, and smart grids are marked out. Furthermore, classical control approaches and adaptive control methods are fully surveyed. Moreover, modern control approaches such as optimal control theory, robust control, and soft computing based control technique are reviewed for load frequency control in power systems. Finally, some research gaps and direction in the topic of modern load frequency control systems are presented.

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Abbreviations

The following abbreviations are used in this manuscript:

ABC	Artificial bee colony
ACE	Area control error
AE	Aqua electrolyzer
AGC	Automatic generation control
BFO	Bacterial foraging optimization
BIA	Bat inspired algorithm
CS	Cuckoo search algorithm
DE	Differential evolution algorithm
DG	Distributed generation
DISCOs	Distribution companies
EVs	Electric vehicles
FA	Firefly algorithm
FACTS	Flexible AC transmission system
FC	Fuel cell
GDB	Governor dead band
GENCOs	Generation companies
GRC	Generation rate constraint
IAE	Integral of absolute error
ITAE	Integral of time multiplied by absolute error
ISE	Integral of squared error
ITSE	Integral of time multiplied by squared error
ID	Integral derivative
IDD	Integral plus double derivative
ISO	Independent system operator
PID	Proportional-integral-derivative
PIDD	Proportional-integral plus double derivative
PIDF	PID with filter
PSO	Particle swarm optimization
QO	Quasi oppositional
QOHS	Quasi-oppositional harmony search algorithm
SOA	Seeker optimization algorithm
STC	Self-tuning control
SOA	Seeker optimization algorithm
LFC	Load frequency control
LUSTLBO	hybrid local unimodal sampling and TLBO algorithm
MIMO-PID	Input-multiple output PID
TRANSCOs	Transmission companies
TLBO	Teaching-learning-based optimization
RERs	Renewable energy resources
PV	Photovoltaic
WAMCS	Wide-area measurement and control systems
WDO	Wind driven optimization algorithm
WTG	Wind turbine generator

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