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REVIEW ARTICLE

# A Comprehensive Review of Recent Strategies on Automatic Generation Control/Load Frequency Control in Power Systems

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## Abstract

This review article aims to provide an in-depth analysis of the literature along with comprehensive bibliography on automatic generation control (AGC)/load frequency control investigations. Different control perspectives concerning frequency and power control have been featured. Diverse linear, non-linear power system models are discussed under conventional and deregulated environments considering various power generation sources, including conventional, renewable energy sources (RES), and realistic RES. Moreover, AGC literature briefly explains various secondary controllers like integer order, fractional order, intelligent, cascade, and some recently used controllers. To obtain the optimum values of secondary controllers, various optimization strategies such as numerical approach, heuristic, and meta-heuristic techniques for AGC issues are mentioned. Also, AGC studies concerning power transmission, considering inertia and phase-locked loops in high voltage direct current (HVDC) and accurate HVDC models are discussed. Further, AGC literature integrated with flexible alternating current transmission system devices in loaded transmission lines and energy storage devices due to intermittent power generation in RES is deliberated. Furthermore, various performance index criteria (PIC) such as standard PIC and hybrid peak area (HPA)–PIC for controller optimization with algorithms are also conferred.

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### Abbreviations

| | |
|---|---|
| AC | Alternating current |
| ACE | Area control error |
| AGC | Automatic generation control |
| AHVDC | Accurate high voltage direct current |
| DC | Direct current |
| DSTS | Dish-Stirling solar thermal system |
| EA | Evolutionary algorithm |
| ESD | Energy storage devices |
| FO | Fractional order |
| FACTS | Flexible alternating current transmission system |
| GDB | Governor dead band |
| GRC | Generation rate constraints |
| HPA | Hybrid peak area |
| IO | Integer order |
| ISE | Integral squared error |
| ITSE | Integral time squared error |
| IAE | Integral absolute error |
| ITAE | Integral time absolute error. |
| LFC | Load frequency control |
| PIC | Performance index criteria |
| PS | Power system |
| RT-Lab | Real-time lab |

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|---|---|
| RES | Renewable energy sources |
| SCIG | Squirrel cage induction generators |
| STPP | Solar thermal power plant |
| SSE | Steady state error |
| NS | Not settled |

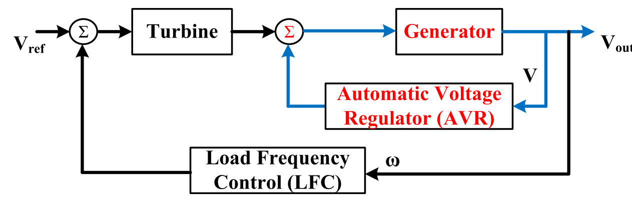



**Fig. 1** AGC with LFC and AVR loops

## 1 Introduction

Regulation of frequency and tie-line power are the critical challenges in an interconnected power system (PS) where manual control is not feasible [1–3]. Also, achieving a precise matching of the generated power to the load at a nominal state is a challenging problem [4–7]. This mismatch is mitigated by the automatic operation of the valve or gate position of the turbine, and this can be accomplished by an automatic generation control, AGC [8–10]. To match the real power demand, the water or steam input of the turbine is to be adequately regulated [11, 12]. The prime mover governing systems provide a means of controlling power and frequency as a function commonly referred to as AGC or automatic load frequency control, LFC [13–18]. The AGC study for large and complex interconnected PSs divides the whole system into various control areas [19–21]. A control area is a PS component in which all the generators operate in unison and are characterized by the same frequency [22–25]. The control area maintains each area's power demand and the system's overall frequency in a regular steady-state operation [26–34]. During load perturbations, each control area maintains its frequency and tie-line power by minimizing the area control error (ACE), which combines frequency and tie-line power deviations [35–40]. Nowadays, investigations have been carried out on AGC of multi-area systems considering multi-control areas [41–43]. Their primary objective is to keep frequency and tie-line power at predetermined values.

The LFC loop maintains the megawatt output and the frequency, which is the governor's speed. This LFC loop comprises two independent loops: the primary loop and the secondary loop [44–46]. The primary control loop responds to frequency signals and is faster [47–49]. On the other hand, the secondary loop is a slower loop that deals with fine frequency adjustments and ensures proper megawatt interchange across different control areas [50–54]. This does not respond to rapid/sudden variations in frequency and tie-power deviations, unlike the primary loop [55–57]. After the primary loop has completed its task, the secondary loop is activated [58–62]. Thus, proper controller design is required to efficiently operate AGC control loops [63–65]. An effective secondary controller is vital to suppress the undesirable deviations and regulate ACE to zero [66–69]. The AGC system comprising of LFC and automatic voltage regulator loop is shown in Fig. 1 [70–72]. Also, AGC study systems considering non-linearity like GRC, and GDB are carried in [73–75]. Moreover, advanced AGC studies are stated with renewable integrated like wind [76], solar thermal [77, 82], electric vehicle [78], solar [79–81], dish Stirling [83–87].

The restructured/deregulated PS is a modification of a conventional/traditional AGC PS that includes proper planning and operation [88, 89]. The conventional PS featured a "vertically integrated utility" (VIU) which served as a single utility comprising a generator, transmission, and distribution utilities [90]. Whereas in deregulated PS, the VIU is absent, and it comprises three different entities like generation companies (GENCOs), transmission companies (TRANSCOs), and distribution companies (DISCOs) [91, 92]. The independent system operator, ISO [91] in deregulated PS provides the bidding rules and regulations among GENCOs and DISCOs under the transactions like poolco, bilateral and contract violation [93–95]. In poolco based transactions, the DISCOs interact with the GENCOs of the same control area [96, 97]. However, in a bilateral-based transaction, the DISCOs from any area can interact with any GENCOs that may or may not belong to the same control area [26, 98–100]. The DISCOs may seek more than the contracted amount [101–103]. During such scenarios, the GENCOs in that control area manage the extra demand by the DISCOs of the same area [104–107]. This additional demand is treated as local load rather than contracted load [108–111]. This scenario is referred to as a contract violation. The DISCO participation matrix (DPM) is used to establish the relation between DISCOs and GENCOs [96, 112, 113]. The elements in DPM are known as the contract participation factor (cpf). The number of GENCOs and DISCOs in the DPM matrix is determined by the rows and columns numbers, respectively [92] and [96].

The secondary controller's activity is critical in an interconnected AGC system [114–116]. The valve point and on–off timing authority of various generating units are managed by a variety of controllers [117, 118]. By minimizing ACE, these auxiliary controllers reduce the steady state error, SSE [119, 120]. For conventional and deregulated AGC system, controllers like integer order (IO) like PI, PID [115, 117], PIDN [118, 119]; intelligent like fuzzy [120–125]; neural [126–128, 146, 147]; fuzzy type-II [129–131]; neuro-fuzzy [132–134, 136, 137]; degree of freedom, DOF [24, 53, 138–142, 162–164]; cascade [27, 28, 40, 59, 69, 78, 143, 144, 162]; tilt [28, 79]; model predictive controller, MPC [148, 149, 151, 152]; optimal MPC [153, 154]; sliding mode controller [156–158] and fractional order, FO [120] like FOPI, FOPID [165], FOPIDN [166]; are proposed for AGC system. These controllers help in minimizing the ACE that helps in achieving SSE [145, 160].

The AGC system concert can be heightened by the solicitation of soft computing approaches by proper setting of controller parameters. Soft computing performances like gradient, direct, Newton–Raphson twig at confined optima and contributes less convergence [55]. On the other hand, Evolutionary techniques like grey wolf [167]; genetic [168, 169]; differential search [170, 171]; gases Brownian [172]; harmonic search [173]; multi-verse [174]; bacterial foraging [175, 176]; grasshopper [177]; artificial bee [178]; whale [179]; ant colony [180]; biogeography [181, 182]; cuckoo search [183]; imperialistic competitive [184–186]; teaching learning [187]; bat [188]; dragon fly [189]; etc., provides global optima and are utilized for AGC studies.

The depletion of conventional energy sources and their negative impacts on the environment has led to the penetration of renewable energy sources (RES) in modern-day PSs [150, 159, 173]. RES are highly abundant in nature and has less impact on the environment with increased energy conversion efficiency [190]. Due to their widespread availability, wind and solar dominate over other RES [191, 192]. Recent literature presents modern solar energy technologies, but they are limited to stand-alone and two-area systems [193, 194]. Also, in the previous few decades, wind energy conversion systems have been widely used in PS research. Only a few studies on the AGC of interconnected systems incorporating solar thermal and wind systems are reported [55]. Further, the AGC studies integrating solar and wind systems have only utilized a first-order transfer function model. Furthermore, realistic models of RES are developed, but they are limited to isolated systems only [55–57]. Thus, in modern PSs, the integration of RES realistic models provides scope for interconnected AGC systems.

The load demand in the PSs is increasing drastically with the increase in population. This increase in load demand requires enhancing power transfer capability in inter-area AGC PSs [195, 196]. To achieve this, high-voltage direct current (HVDC) tie-lines are added in parallel with the present AC tie-lines and the integration of flexible AC transmission system (FACTS) devices among the control areas [197]. With the development of HVDC tie-lines and FACTS devices, many researchers were interested in improving the power transfer capabilities by providing flexible operation and control in AGC studies [198–200]. HVDC and FACTS devices play a key role in improving the system performance in terms of real power flow, real power loss minimization, and damping ratio improvement resulting in a low number of oscillations, and lesser values of peak overshoots, and quick settling time [201–205]. The right selection of FACTS controller from among the different available options and its ideal location in the PS is a critical decision [206, 207]. Also, recent literature in AGC studies presented the development of an accurate HVDC (AHVDC) tie-line model, but it is restricted to isolated and two-area systems only [55–57]. Thus, integrating the AHVDC tie-line model [208, 209] with the FACTS device [19, 210, 211] in modern PSs provides scope for interconnected AGC systems.

The power output of RES is variable, fluctuating, and unpredictable, which might cause varying power supply [212, 213]. Hence, to mitigate this, energy storage devices (ESD) like battery systems [214, 215]; flywheel [217, 218]; capacitive energy systems [219]; superconducting magnetic energy storage [216]; ultra-capacitor, UC [18, 40, 49]; and redox flow batteries, RFBs [37, 48], etc., can be integrated to ensure that power is delivered to the load continuously while maintaining a low system cost. Thus, ESD has found its application in the AGC study.

Studies considering interconnected AGC PS integrated with RES, linearity or nonlinearity parameters, excitation control considering various secondary controllers, parallel AC/DC transmission, FACTS devices, ESD and HPA–PICs are augmented with AGC problems from time to time along with appreciated research contributions [220]. The optimal amendment of its parameters can enhance the controller efficiency. Optimal tuning can be achieved by traditional and EA's.

Recent advancements in the AGC field involve the development of realistic models of RES, application of modern control techniques and cascade controllers like IO–IO, FO–FO, IO–FO, IO-fuzzy, FO-fuzzy, neuro-fuzzy, 2DOF, 3DOF–TID etc., Moreover, studies comprise new performance indices namely HPA–PIC over conventional PICs like ISE, ITSE, IAE, and ITAE. Further, meta-heuristic algorithms are required to tackle the optimization of various secondary controllers. Apart from advancements in control principles, several developments have occurred in the previous decade such as deregulated PS market, utilization of FACTS, ESD, fuel cells and mathematical modeling of AHVDC tie-lines. As a result, the new AGC control theories have evolved to put up the implications on system dynamics. This study focuses on how the AGC system incorporates the RES, secondary controllers, FACTS, ESD, and PICs. It also presents a detailed review of AGC on soft computing approach with distant algorithms considering both conventional and deregulated PS.

### 1.1 Novelty and Contribution

Given the above, the novelties of the study are as follows:

- The modern AGC techniques that can be used to combine RES with HVDC interconnection, FACTS devices, and various ESD are discussed.
- Application of soft computing techniques on AGC studies that can manage non-linearities and parametric changes in various load disturbances are presented.
- AGC systems facilitating the integration of high intermittent distributed generation sources considering various microgrid configurations in a stand-alone or single-area and multiple area concepts are analyzed.
- Competent deregulated AGC models can improve the restructured power market's economic efficiency deliberated.
- Industrial practices of various AGC models worldwide investigate and analyze various difficulties linked to their practical application in the field.
- Optimization of controller parameters in AGC studies based on HPA–PIC is demonstrated.

Thus, the main contributions of this review article are as follows:

- The evolution of the AGC system under conventional and deregulated thermal PSs integrated with RES considering nonlinearities like GDB, GRC, parametric variations, time delay concerns, inertial response, and observability of state variables are explored.
- The concept of a multi-area AGC system with different PICs is presented from the literature based on objective functions and is used to reduce the ACE.
- State-of-the-art AGC schemes are presented for the existing and future intelligent PSs, aiming at classical and modern control techniques. Also, AGC techniques with fuzzy neural networks along with soft computing techniques are demonstrated. Moreover, the benefits and drawbacks of these control methods are contrasted in a tabular form.
- A detailed literature assessment is also provided on AGC techniques, including various ESD, HVDC interconnections, and FACTS devices.

## 2 Overview of AGC/LFC

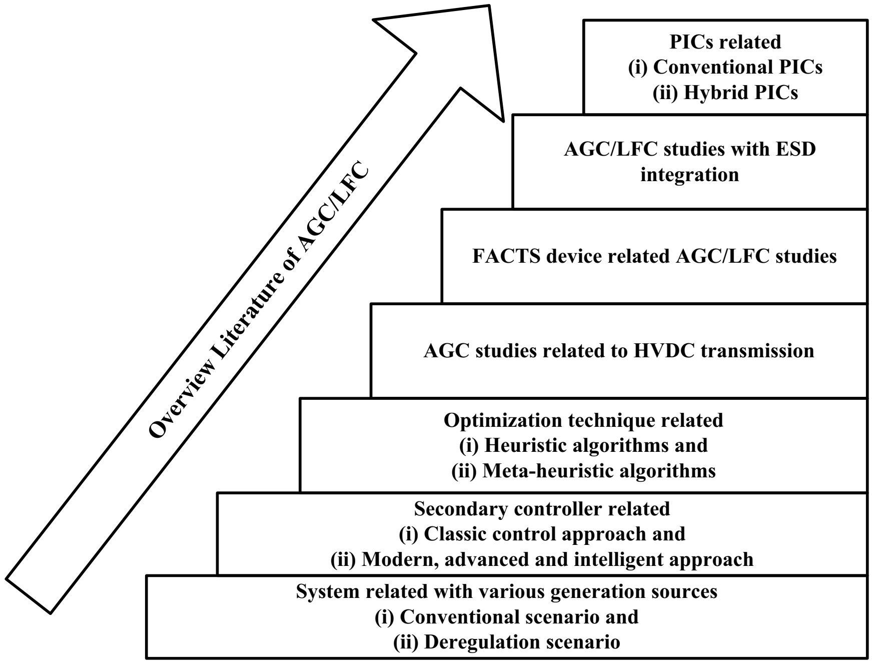
The initial attempt in the field of AGC was to control the PS frequency using the synchronous machines flywheel governor. Later, it was discovered that the frequency control strategy is inadequate. An additional secondary controller with a multi-area concept considering tie-line power was incorporated using a feedback signal proportional to the frequency and tie-power deviations. These controllers effectively adjust ACE to zero. This establishes a conventional approach to the AGC systems. Initial studies with frequency and tie power deviation are developed by Cohn et al. [4, 5]. Quazza et al. [6] proposed a control area concept in which each control area is responsible for its load variations. Elgerd et al. [7] pioneered the optimal control approach for AGC/LFC controller design in interconnected PS. Primary AGC studies with optimal controller values are attained by the trial and error method followed by the numerical method approach and heuristic/meta-heuristic algorithms. The consecutive AGC works are carried out with RES, ESD, and FACTS device integration that provides better system dynamics during disturbances and can store and transfer power in bulk capacities. Nowadays, AGC studies mainly concentrate on developing realistic or accurate models of RES and FACTS devices and their integration with RT-Lab simulation. The schematic and flow diagram of the overview literature of AGC is shown in Fig. 2a and b, respectively.

## 3 Detailed Literature Review on Various Categories

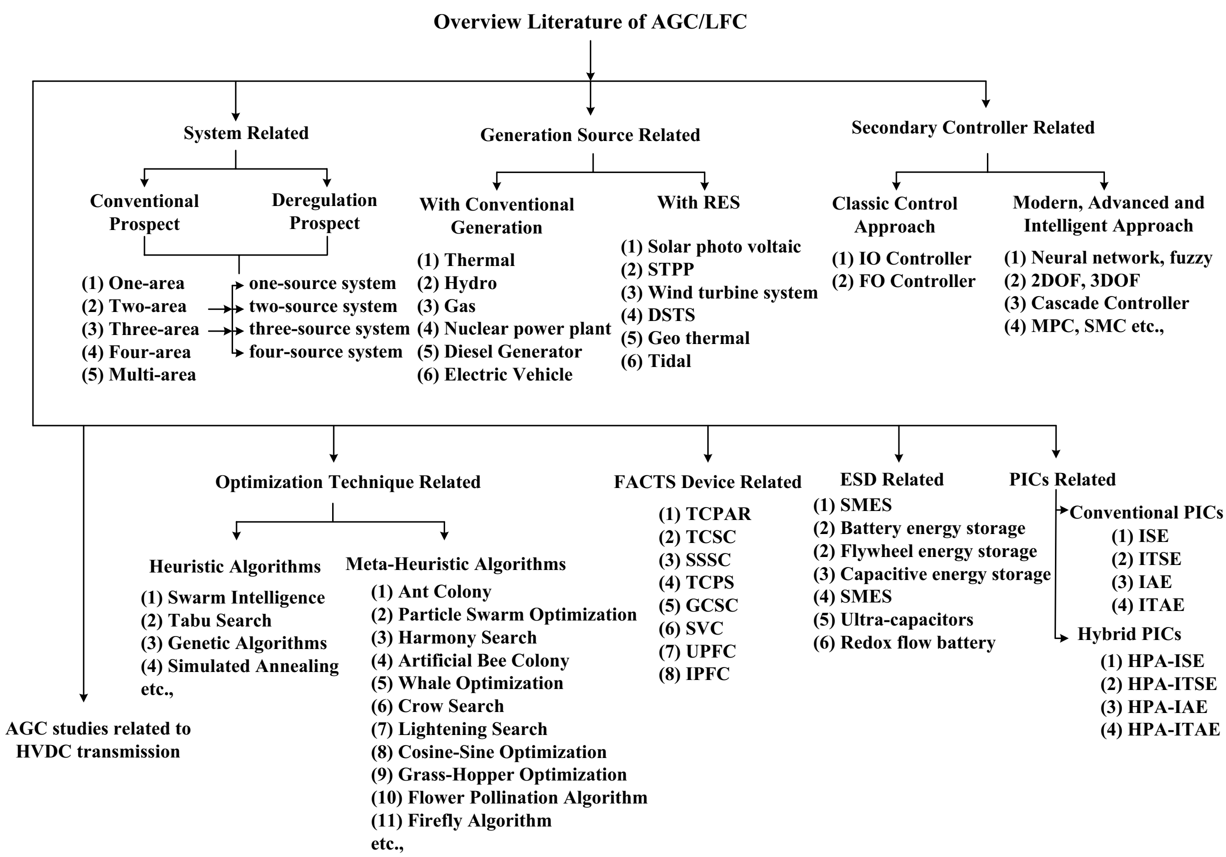
The AGC issue has been managed broadly over five decades, and it mainly comprises linearized models [2, 4–9]. For analyzing the system reaction, the AGC system is modeled by small-signal analysis considering small perturbations. However, using a linearized AGC model to control a non-linear system does not ensure the PS stability, which gained significance. Later on, nonlinearities like GRC, and GDB are included in both continuous and discontinuous PS models [7, 10, 11]. These non-linearities contribute to consecutive oscillations in frequency and tie-power. Kwatny et al. [12] developed an optimal PID control tracking method in AGC by incorporating energy source and load as output.

### 3.1 AGC/LFC Under Conventional Scenario

The interconnected PS is typically large with generating stations, load centres and complex dynamic structures linked together. From generation, transmission and distribution (GTD) of power, traditional/conventional form of PS has been used with conventional sources like hydro, thermal, gas and nuclear [13–45]. The AGC studies are initiated with single-area traditional PS with linearized model of thermal system [2, 4–9]. Later on, AGC studies are carried with conventional sources like hydro [13–20]; gas [21–27]; nuclear [24, 28, 29]; diesel generator [30–39]; and electric vehicle [28, 40–44]. Further, the single area [1, 2, 45]; AGC studies are extended to two area–one source [39, 46]; two-area–two source [16, 47, 48]; two area–three source [28, 49, 50]; three




(a) Schematic diagram of overview literature of AGC/LFC




(b) Flow diagram of overview literature of AGC/LFC

**Fig. 2** **a** Schematic diagram of overview literature of AGC/LFC. **b** Flow diagram of overview literature of AGC/LFC area–one source [51–54]; three area–two source [55–58]; three area–three source [31, 32, 59, 60]; four area–one source [20, 61] and multi area–multi-source systems. The block diagram conventional single/one/isolated, two and three-area and multi-area AGC systems are illustrated in Figs. 3 and 4 respectively.

However, in the twenty first century, RES like wind [13, 14, 32–34, 39, 62–66], tidal [67, 68], geothermal [14, 26, 58, 59, 69, solar photo voltaic [70–75], DSTS [26, 31, 48, 59, 62, 76, 77] and STPP [32, 47, 57, 78, 79] are integrated to form a distributed generation, due to the eco-friendly pollution, disintegration and expense of fossil fuels. By RES, energy efficiency can be improved by employing cutting-edge, sophisticated procedures with lower environmental impact [80]. The idea of RES inclusion in AGC was initiated by [81]. Bervani et al. [81] developed a solar PV system for AGC study in which solar energy is collected by solar panels and stored energy in thermal form with which steam is generated to run the turbine. The grid linking of ocean thermal with solar for AGC study was developed in [37]. The LFC for hybrid systems considering STPP, DSTS with SCIGs connection, and its control strategy is proposed by [82–87]. Author in [14, 26] presented AGC study with geothermal and gas considering thermal systems. AGC Studies involving wind systems are illustrated in [84]. Despite the available RES, the present trend of AGC studies involves the development of RES realistic models [55, 85–87]. The detailed analysis of the AGC system under a conventional scenario with two, three, and four-area

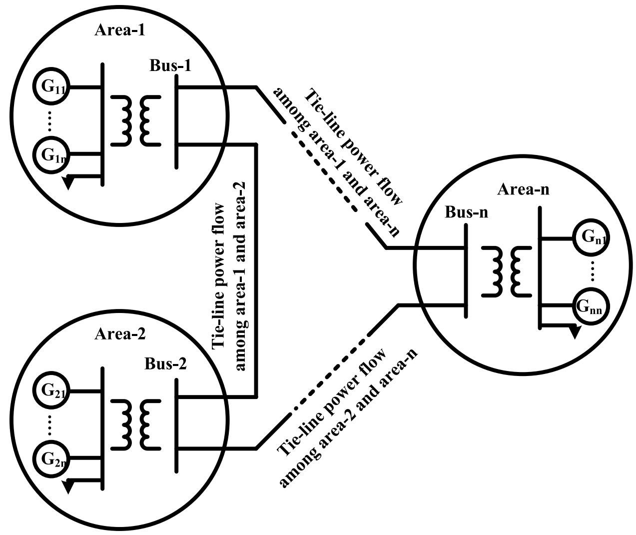



**Fig. 4** Schematic diagram of multi-area interconnected power system

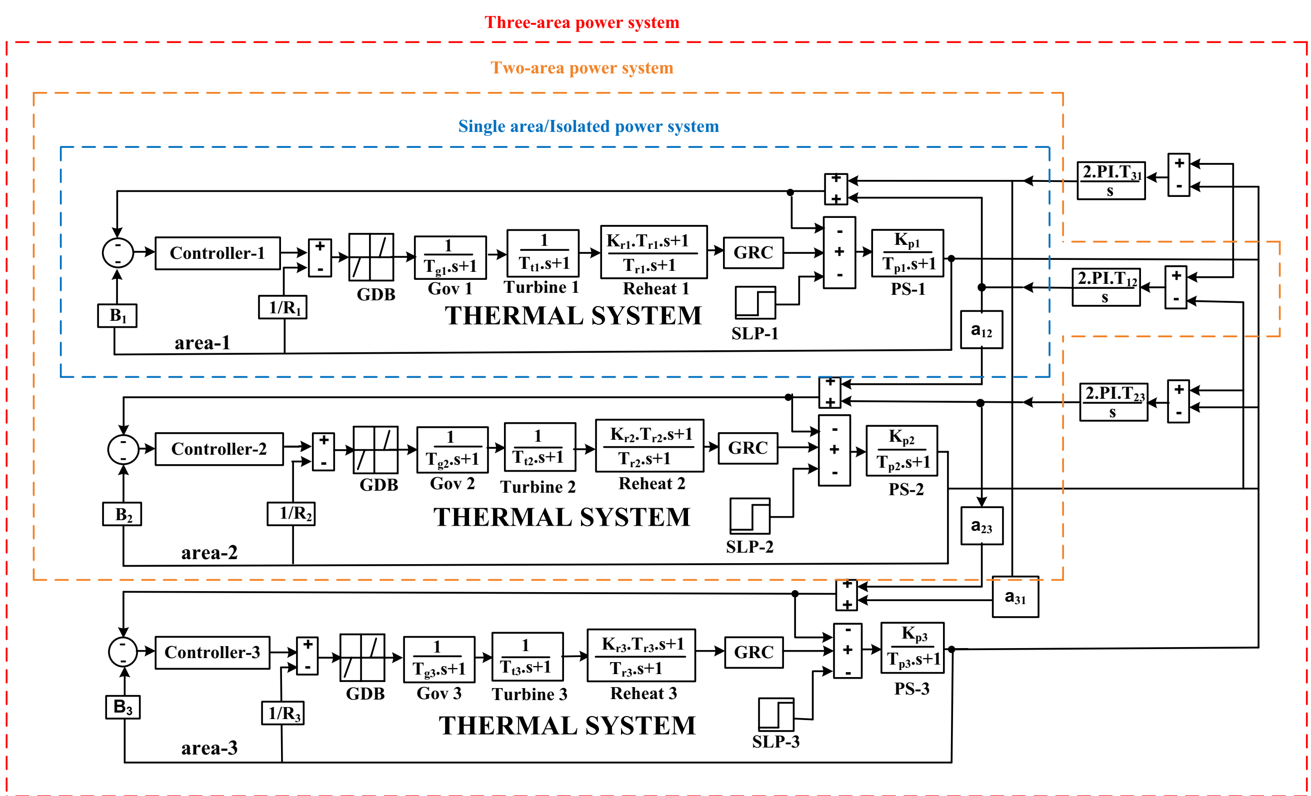



**Fig. 3** Transfer function block diagram of a single, two, and three-area power system

considering various auxiliaries is shown in Tables 3, 5, and 7, respectively.

### 3.2 AGC/LFC Under Restructured/Deregulated Scenario

Electricity restructured/deregulated market is the practice of altering the regulations and laws that govern the electric business so that customers choose electricity suppliers that are either retailers or traders. It boosts the efficiency and economy of electricity production. Energy prices are projected to fall due to increased competition that benefits the customers. In a deregulated electricity market, the traditional ACE-based LFC is challenging to apply. Lately, a few control strategies depend on optimal and robust approaches proposed for deregulated AGC PS [88–95].

In the traditional market, a monopoly exists among GTD companies. However, in a deregulated market, there exist more market players. ISO delivers terms among these GTD companies during bidding with various transactions such as bilateral, poolco, and contract violations. This is needed because of unscheduled generation and demand changes, as well as PS unpredictable frequency bias. The demand change in an area generates a frequency change, which makes all the governors in the PS respond quickly, regardless of whether they are chosen for AGC. The basic structure of a deregulated PS comprising GTD companies is shown in Fig. 5. Tables 4 and 6 demonstrate a clear examination of the AGC system under a deregulated scenario with two and three-area configurations, respectively considering various auxiliaries.

Donde et al. [92] established the association among DISCOs and GENCOs by DPM with cpf as its elements. Parida et al. [96] presented a study on AGC in a deregulated market with area participation factor (apf) formed by cpf. Initial conventional/deregulated AGC works started with two-area and extended to three-area thermal systems with the integration of RES, FACTS, and ESD devices. RES such as DSTS, WTS, STPP, and geo-thermal are considered under deregulated PS market. Deregulated PSs such as two-area–one-source [59], two-area–two-source [70], two-area–three-source [76], two-area–four-source [140], and extended to three-area–one-source [221], three-area–two-source [26] and three-area–three-source [69] thermal are studied. Fewer studies are found with a four-area deregulated PS.

The present trends of AGC under deregulated environment involve the utilization of meta-heuristic techniques for optimization and the design of various cascade secondary controllers considering new HPA–ISE as an objective function for reducing the ACE. Moreover, deregulated studies include realistic models of generating systems and FACTS devices. The transfer function block diagram of a two-area–two-source deregulated AGC system comprising four GENCOs and four DISCOs is shown in Fig. 6. Few AGC/LFC literature comprising conventional and deregulated systems considering various control techniques, RES, and optimization techniques are noted in Table 1.

### 3.3 Secondary Controller Related AGC/LFC Studies

Pioneer AGC issues in PS are addressed with centralised control approach [6, 7, 97, 98]. Several control techniques are proposed based on disturbance classes [6]. Authors in [7, 9, 97] proposed a feedback controller structure to eradicate the disturbance and also suggested an

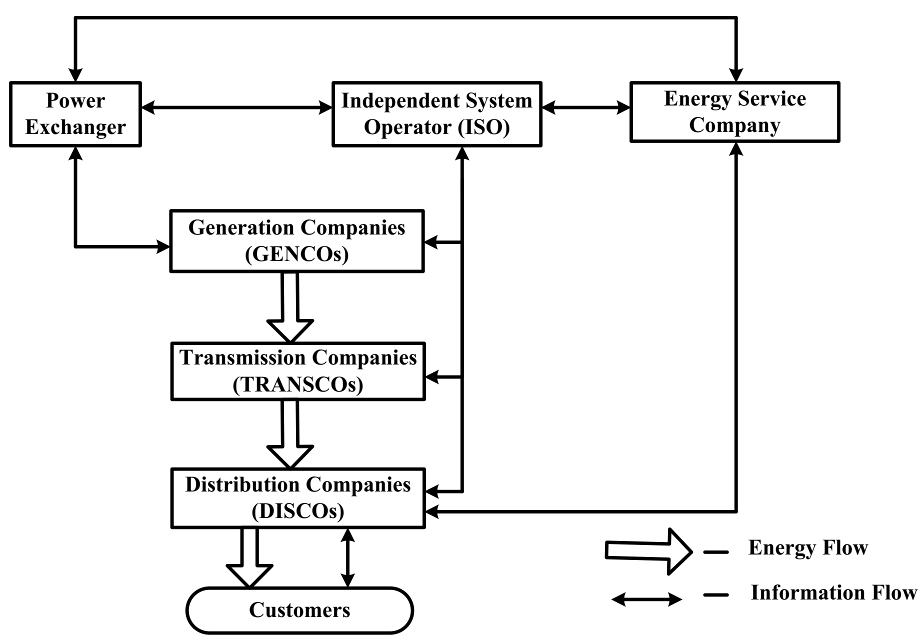



**Fig. 5** Basic structure of a deregulated power system

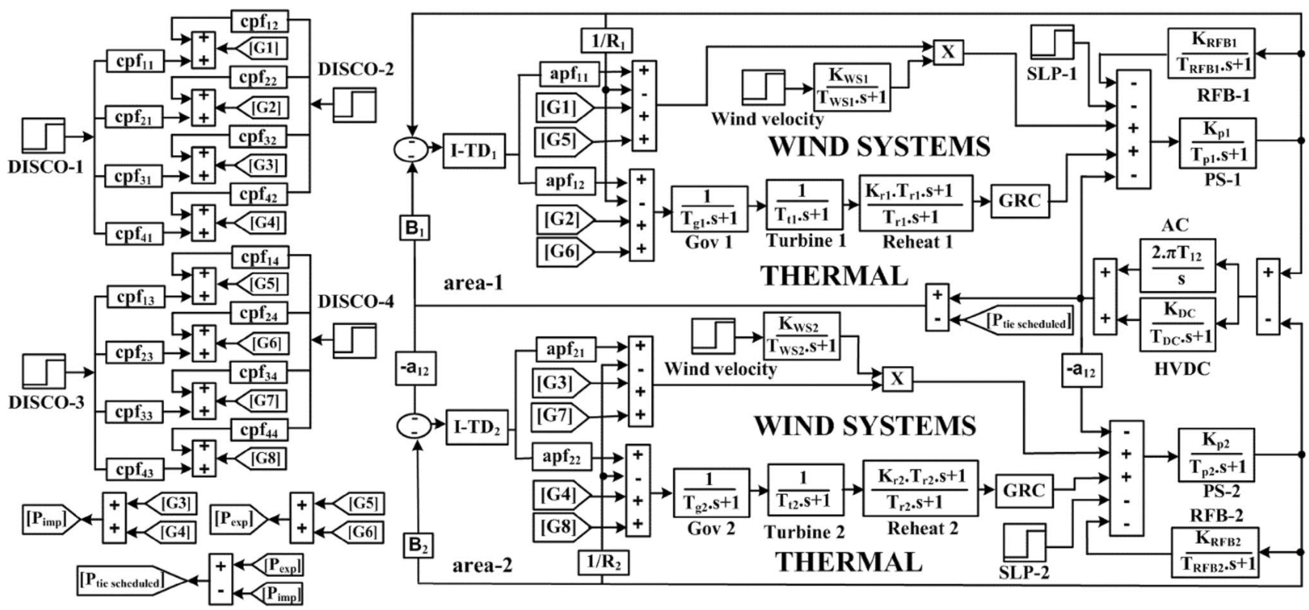



**Fig. 6** Transfer function diagram of a two-area thermal–DSTS system under deregulated scenario [221]

optimal control strategy assuming deterministic load disturbances by ignoring steady-state errors (SSE). The main drawback of information exchange among control areas over indistinctly connected topographical territories with increased computational techniques tends to be a decentralized control approach. This PS approach solves such problems effectively by considering discrete and continuous PS models [99–105]. Authors in [106] presented a decentralized AGC study considering structural properties like controllability and observability for interconnected PS models. The proposed decentralized scheme senses the control loops to be decoupled and suggests an approach of total decentralization of global feedback control policy. Once more, a class of orderly disseminated controllers is designed based on (i) centralized controller design with dispersed implementations, (ii) dynamic systems model reduction and (iii) interactions among the subsystems that make up the modeling of the global control system [107]. The brilliance in controller design is that it achieves nearly equal results as the centralized one.

Based on the above, various AGC controller methods such as two and multi-level techniques have been documented. The two-level control technique does not ensure zero SSE, whereas, the multi-level control technique ensures zero SSE [108–110]. The AGC/LFC problem has also been solved using a global controller that takes advantage of the potential benefit of interconnectivity [111]. Later on, the concept of SLP is introduced with the decomposition of the system into a fast and slow subsystem that develops a composite controller. The independent controllers for fast and slow sub-systems were merged so that the slower subsystem continuously relates to the faster subsystem at the moment, and the studies are carried out on large PS with GRC inclusion [112]. Further, with technological advancement, many controllers are developed for AGC problems.

### 3.3.1 Classical Secondary Controllers for AGC/LFC Study

Classical controller approaches like IO and FO are considered for AGC study. Controllers such as integral (I) controller [9, 113, 114] double derivative (DD) controller [115] are proposed to reduce the SSE and to improve the system's stability. AGC studies in [62, 116] utilized Proportional-I (PI) controller to eliminate the SSE. Later, PID controller is proposed to boost the overall system performance [49, 62, 74, 117]. From the studies in [35], it is evident that PID controller with filter (PIDN) controller is superior over other controllers. The presence of D-term in the feedback path generates disturbance. To avoid this, the authors designed a PIDN coefficient for AGC studies [35]. Moreover, various forms of PIDs such as PIDD [118], IDDN [30], I-PDN [13] etc., are also proposed for AGC studies to enhance the system dynamics over conventional PID controllers. With zero tuning parameters in IO controllers, the PS is less stable. To improve PS stability, authors have proposed FO controllers with lambda (λ) as an integral parameter and mu (μ) as a differentiator parameter. FO controllers such as FOPI [55], FOPID [119], and FOPIDN [56] are suggested for AGC literature and are observed that the FOPIDN controller shows its superiority over all the mentioned controllers [56]. Also, tilt (T) controllers such as TID, I-TD [28, 79] are suggested for AGC studies that enhance dynamics over IO controllers.

**Table 1** Summary of AGC/LFC literature with and without RES and auxiliaries

| References | Conventional /deregulated | Area number | System description | RES | Control technique | Algorithm | Auxiliaries |
|---|---|---|---|---|---|---|---|
| [28] | Conventional | 2-Area | Area-1: Thermal, Hydro, Nuclear Area-2: Thermal, Hydro, nuclear | – | TI–TD | Water cycle algorithm | EV |
| [76] | Conventional | 2-Area | Area-1: Thermal, DSTS Area-2: Thermal, WTS | DSTS, WTS | PID | Biogeography based optimization | – |
| [78] | Conventional | 3-Area | Area-1: Thermal, STPP, STP Area-2: Thermal, SHPP, EV Area-3: Thermal, SHPP, EV | SHPP, STPP, EV | IDN–FOPD | Whale optimization algorithm | – |
| [13] | Conventional | 3-Area | Area-1: Wind Area-2: Thermal Area-3: Hydro | Wind | I-PDN | Stochastic Fractal Search | FACTS |
| [14] | Conventional | 3-Area | Area-1: GTPP, Thermal, Hydro Area-2: Thermal, Wind Area-3: Thermal, STPP | Wind STPP | FOPI–FOPID | Sine–cosine algorithm | ESD |
| [15] | Conventional | 3-Area | Area-1: DG, Thermal Area-2: Thermal, Area-3: Hydro | DG | FOPID | Hybrid ALO–PSO | HVDC Link |
| [17] | Conventional | 3-Area | Area-1: Thermal Area-2: Thermal, Hydro Area-3: Thermal | – | FFOPI–FOPD | Imperialist competitive algorithm | – |
| [79] | Conventional | 3-Area | Area-1: Thermal, STP Area-2: Thermal, Thermal Area-3: Thermal, WTS | STTP, WTS | I-TD | Grasshopper algorithm | – |
| [20] | Conventional | 4-Area | Area-1: Thermal Area-2: Thermal Area-3: Thermal Area-4: Hydro | – | Fuzzy PID | Self-Adaptive Modified Bat Algorithm | – |
| [25] | Conventional | 5-Area | Area-1: Thermal, Hydro, Gas Area-2: Thermal, Hydro, Gas Area-3: Thermal, Hydro, Gas Area-4: Thermal, Hydro, Gas Area-5: Thermal, Hydro, Gas | – | PID | Quasi-oppositional harmony search | – |
| [34] | Deregulated | 2-Area | Area-1: Thermal, wind Area-2: Thermal, DG | Wind, DG | $PID^{\mu}N$ | Lightning search algorithm | FACTS |

**Table 1** (continued)

| References | Conventional /deregulated | Area number | System description | RES | Control technique | Algorithm | Auxiliaries |
|---|---|---|---|---|---|---|---|
| [66] | Deregulated | 2-Area | Area-1: DFIG, WTS<br>Area-2: DFIG, WTS | DFIG, WTS | PI | Moth-flame optimization | ESD |
| [118] | Deregulated | 2-Area | Area-1: Thermal, Hydro, Nuclear<br>Area-1: Thermal, Hydro, Nuclear | – | PIDD | Fruit fly algorithm | – |
| [124] | Deregulated | 2-Area | Area-1: Thermal<br>Area-2: Hydro | – | FLC | Genetic algorithm | – |
| [140] | Deregulated | 2-Area | Area-2: Thermal, Thermal<br>Area-2: Hydro, Gas | – | 2DOF–TID | Grasshopper algorithm | HVDC, EES, PLL |
| [26] | Deregulated | 3-Area | Area-1: Thermal, GTTP<br>Area-2: Thermal, GAS<br>Area-3: Thermal, GAS | GAS | FOPI–FOPD | Sine–cosine algorithm | ESD |
| [43] | Deregulated | 3-Area | Area-1: Thermal, Hydro, Gas<br>Area-2: Thermal, Hydro, Gas<br>Area-3: Thermal, Hydro, Gas | EV | $PI^{\lambda}D^{\mu}$ | Flower pollination algorithm | – |
| [56] | Deregulated | 3-Area | Area-1: Thermal, RDSTS<br>Area-2: Thermal, RDSTS<br>Area-3: Thermal, RDSTS | RDSTS | FOPDN–FOPIDN | Crow search algorithm | HVDC |
| [119] | Deregulated | 3-Area | Area-1: Thermal, Thermal<br>Area-2: Thermal<br>Area-3: Thermal | – | FOPID | Bacterial foraging algorithm | – |
| [38] | Deregulated | 4-Area | Area-1: Thermal, Hydro, Gas, DG<br>Area-2: Thermal, Hydro, Gas, DG<br>Area-2: Thermal, Hydro, Gas, DG<br>Area-3: Thermal, Hydro, Gas, DG | DG | PID | Modified virus colony search | – |

This is because of the availability of more tuning parameters in the FOPIDN controller.

### 3.3.2 Modern/Advanced and Intelligent Secondary Controllers for AGC Study

Due to advancements in technology, modern controllers such as fuzzy controllers [120–131], neural networks [132–134], DOF [135–142], and cascade controllers [143–147] are available in AGC literature.

**3.3.2.1 Intelligent Secondary Controllers** In contrast to the conventional control approach with a linearized mathematical model, the authors in [120] suggested a fuzzy logic control strategy (FLCS). It is based on the system's experience and information with an accurate and sufficient knowledge base. This FLCS is mainly used for uncertainty problems. The fuzzy controller's application, structure, and operation with AGC are discussed in [112, 121]. Later, FLCS is applied to the thermal system along with various RES and ESD units [122, 123]. Moreover, the application of FLCS for multi-area PS under deregulated environment is presented in [124]. AGC study in [125, 126] presented a novel fuzzy theory-based control approach to enhance the short-term PS frequency capability. Also, an optimal tuned FLCS is proposed to suppress frequency and tie-line deviations for a multi-stage optimization [63]. To attain the fine-tuning approach, a robust FLCS is proposed and is validated in [127]. An intelligent FLCS is developed to support controllable loads and generation units [128]. A type-2 FLCS is proposed to reduce the oscillations damping using FACTS devices and feedback control technique [129–131]. The limitation of the FLCS technique is that as PS complexity increases, the membership function increases along with computational time. Taking security as an essential aspect, authors in [58, 132] proposed a novel controller structure named artificial neural networks (ANN) considering the biological nervous system with a data classification technique for an isolated PS AGC network. Ogbonna et al. [133] proposed an ANN for restructured AGC system and compared the responses with conventional controllers and it is found that ANN generates a better dynamic. A non-linear periodic ANN structure is suggested for the LFC study and it is evident that PS stability has enhanced [134].

**3.3.2.2 Higher Degree of Freedom (DOF) Secondary Controllers** The closed-loop transfer function that can be changed autonomously is the DOF control. The 2DOF controller comprises two signals, and its design is based on the change among the reference and measured signals [135]. These two input signals with weighted values show more advantages over conventional controllers. The 2DOF controller calculates a weighted change in signal for the respective controllers based on the stated set points. Every signal action is weighted rendering to the selected gains [135]. Controllers such as 2DOF–PID [136–138], 2DOF–IDD [139], 2DOF–TID [24, 140] are considered for AGC/LFC studies. 2DOF, and 3DOF controllers enhance system dynamics over conventional controllers. Considering the disturbance elimination factor in a 2DOF controller, a 3DOF–PID controller was suggested for AGC/LFC study [52, 141], and [142], and it is observed that the 3DOF controller enhances PS dynamics over 2DOF controllers.

**3.3.2.3 Cascade Type Secondary Controllers** Cascade control is the outcome of two successive processes. It has more advantages over one control loop system. The outer loop and inner loops are known as master and slave controller loops. It is designed such that the output of the outer loop is the input of the inner loop. It is mainly used for disturbance rejection at a faster rate. The outer and inner loops control the quality of the final output and attenuate the disturbances [143]. Saikia et al. first proposed the cascading of IO–IO, IO–FO, FO–FO and IO-intelligent controllers for AGC studies. Cascade controllers such as PID–DD [115], PI–PD [144], FOPI–FODN [55], FOPDN–FOPIDN [56], FOPI–FOIDN [57], FOPI–FOPD [26, 27], FOI–FOPID [69], FOPI–FOPID [14, 59], PIDN–FOPD [47], PIDN–FOID [48], IDN–FOPD [78, 145] are suggested for AGC/LFC studies. Further, cascade controls with the intelligent controller are also stated in [146, 147]. The obtained systems responses with cascade control are linked with various optimization techniques is evident that the PS shows better dynamics over all the conventional, DOF and intelligent controllers.

**3.3.2.4 Some Other Control Techniques** The MPC relates to the ANN technique and works by using garbled elements. It predicts the plant's next reaction based on its recent output. An explicit MPC approach is suggested for improving control performances and calculates the controllable laws for LFC studies used for wind systems [148–150]. MPC technique is also utilized for LFC problems in microgrids with DC links [151, 152]. BIA is proposed for optimal control MPC technique to enhance the damping of oscillations for LFC systems [153]. Further, the MPC technique with artificial intelligence is considered for RES and ESD of the LFC study [154].

Sliding mode control (SMC) is a non-linear control technique that changes the kinetics of a PS considering discrete control signals. Considering the linear and terminal SMCs a full order SMC is developed and is utilized for the LFC problem [155]. Eventual SMC and double SMC are suggested for LFC problems considering RES in the micro-grid system [156]. A non-linear H∞ based SMC is proposed for three-area LFC systems [157].

The MPC and SMC techniques are mostly utilized for uncertainty in power generation. Further, a variable structure control approach, adaptive control, centralize, and decentralized control techniques are proposed LFC problem in order to improve the system dynamics [158–161]. Authors in [162–166] presented the concept of disturbance observer-aided controller using soft computing techniques to improve the system's overall stability. An overview of all the secondary controllers with their benefits and drawbacks is listed in Table 2. The detailed various control approach in this review paper of an AGC/LFC system with two, three and four-area configurations under conventional and deregulated scenarios are illustrated in Tables 3, 4, 5, 6, 7, 8, and 9.

### 3.4 Various Optimization Techniques Related to AGC/LFC Studies

The performance of secondary controllers will be best when their gains and parameters are optimized or appropriately tuned. It can be achieved by traditional and bio-inspired algorithms/techniques. Traditional algorithms like gradient search, newton method, random search, etc., have drawbacks of slow convergence, spiking at local optima solution, and taking large iterations to obtain an optimum solution. In contrast, bio-inspired techniques or evolutionary algorithms (EAs) like heuristic and meta-heuristic algorithms converge faster with fewer iterations and a global optima solution. Nowadays, EAs are mostly used for the optimization of controller values. The present trends refer to the utilization of EAs for solving non-linear and complex optimization problems. The genetic algorithm was the 1st EA used for controller optimization in AGC studies [167–169]. Later on, several EAs are utilized for optimization depending upon the application, error functions, complexity, faster convergence, and runtime [19–218]. Table 10 shows the benefits and drawbacks of traditional, heuristic, and meta-heuristic algorithms.

The overview of AGC literature is shown in Table 11 and the EAs overview, along with the controllers used for optimization in AGC studies, are listed in Table 12. Further, the present AGC studies refer to the hybridization of existing algorithms.

### 3.5 AGC Studies Involving HVDC Transmission

HVDC transmission has arisen as a viable option for enormous power transmission across long distances due to various economic and technical benefits. In addition, the HVDC connection among the prevailing AC lines has extracted more benefits in terms of PS stability. Significant considerations have been paid to consider the damping impact of a DC system over an interconnected AC line system. The pioneer LFC study considering the HVDC system was demonstrated by Yoshida et al. [196]. LFC works considering 1st order transfer function of HVDC links under conventional and deregulated system was suggested for various LFC problems [15, 31, 59, 120, 175, 196–200]. PS inertia levels reduce to zero due to non-rotating bodies in RES. To accommodate this inertia, the authors proposed and VSC-based inertia considering inertia emulation control (IEC) strategy in HVDC systems [201]. Parameters such as voltage, power rating, DC capacitance value, and its number are not considered in the conventional model of the HVDC system. By considering the parameters mentioned above, authors in [202], and [203] developed an accurate HVDC (AHVDC) model for a two-area conventional LFC system with derivative and integral control. Later Saikia et al. proposed an AHVDC system for a three-area LFC system under both conventional and deregulated environments considering cascade controllers [55–57]. Also, HVDC studies considering phase-locked loops and virtual inertia are carried out for LFC systems [140, 204, 205]. The effect of HVDC integration with the numerical values is shown in Table 4.

### 3.6 Integration of FACTS Devices in AGC/LFC Studies

Flexible alternate current transmission system (FACTS) devices play a vital role in power flow regulation and enhance the power transfer capacity under stable conditions. They are generally connected to overloaded transmission lines. Studies in [206, 207] suggested the appropriate location of FACTS devices to maximize the power considering various optimization techniques in interconnected PS. Desire et al. [208] presented an AGC study considering a thyristor-controlled phase angle rectifier (TCPAR) connected in series with an AC line comprising of frequency stabilizer and power regulator for transient power flow. Authors in [23, 50, 209] demonstrated an AGC study comprising a thyristor-controlled series capacitor (TCSC) that is connected in series with an AC line, which is operated by firing angles. It is used to increase the transmission line active power flow in AGC systems. A static synchronous series compensator (SSSC) is proposed to damp out the sub-synchronous oscillations in an interconnected PS considering a series capacitor [19]. Rajesh et al. [210] suggested a thyristor-controlled phase shifter (TCPS) in series with an AC line to improve transient and dynamic PS stability considering integral control in a two-area LFC system. The accompanying AGC loop gate-controlled series capacitor (GCSC) was connected in series with the AC line, acting as a damping controller. Javad et al. presented a comparative analysis considering TCSC, TCPC, SSSC, and GCSC and suggested that GCSC enhances system dynamics [19, 211]. To control the reactive power in PS static var compensator (SVC) are installed across AC lines [62]. The unified power flow controller (UPFC) is installed in series with the AC line and eliminates transient oscillations with voltage support [212–214]. Dynamics comparisons of UPFC with SSSC and TCPS in LFC studies show better responses over the latter [13]. Later, an interline power flow controller (IPFC) is suggested for the LFC study which is the combination of two SSSC forming a bidirectional power flow and is used for series compensation [32–34, 69, 183]. Deepak et al. [21] performed a comparative analysis over SSSC, TCPS, UPFC, and IPFC in a two-area system and showed that IPFC exhibits better dynamics. The effect of FACTS device integration and its comparisons among them and the numerical values are shown in Table 4.

### 3.7 AGC/LFC Literature Considering ESD

RES such as solar, and wind in PS exhibit intermittent generation, and the decrease in inertia deteriorates PS stability. With this inertial reduction and stochastic nature among generation and load demand in modern PS, LFC has become a crucial contest compared to conventional PS. A practical, fast response ESD improves the PS stability by adding storage capacity, which shares the abrupt load change. Preliminary ESD–LFC works considering lead-acid batteries are presented in [215]. The drawbacks of less expulsion rate, more power reversal time, and maintenance directed to the development of super magnetic energy storage, SMES [21, 190, 216]. The SMES–IPFC LFC study in [34] shows that the power oscillations have reduced substantially over the traditional LFC system. The effect of the battery energy system (BES) on the LFC system is studied by considering non-linearities like GRC and GDB [217]. The properties of high energy density, quick response, and ability to store energy from wind–solar systems make BES superior to others [71]. To stabilize the low and high-frequency power oscillations in PS, flywheel energy storage (FES) systems are suggested in LFC studies. Moreover, LFC studies are carried by considering electric vehicles as energy storage for DC microgrid systems. However, compared to BES, it has a drawback of storing and distributing power over shorter times [218]. Later, capacitive energy storage (CES) is suggested for LFC studies, and it has a quicker response to power deviations over FES [219]. Considering efficiency, longer life, and operating costs, UC is suggested for LFC studies. It is observed that the utilization of UC in all areas enhances system dynamics [47]. Also, rechargeable batteries like RFB has the advantage of long service and quick response with fewer losses and are gaining thrust in LFC studies. Performance comparison among various ESD like BES, CES, UC, SMES, FES, and RFB is evident that RFB outperforms overall ESD [14]. The impact of ESD integration and comparison among various ESD units are shown in Table 6. The transfer function of ESD units considering gain and time constants and their key benefits and drawbacks is listed in Table 13. Its comparative cost analysis is noted in Table 14.

### 3.8 AGC Studies Considering Various PICs

The existing literature on AGC has mostly considered conventional PICs like ISE, ITSE, IAE, and ITAE for controller parameter optimization considering various optimization techniques and their equations are given in (1)–(4) [13–15, 18, 26, 27, 40, 47, 48, 54–57, 122].

$$\eta_{ISE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} (\Delta F_j)^2 + (\Delta P_{k-m})^2 \right\} dt, \quad (1)$$

$$\eta_{IAE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} |\Delta F_j| + |\Delta P_{k-m}| \right\} dt, \quad (2)$$

$$\eta_{ITSE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} (\Delta F_j)^2 + (\Delta P_{k-m})^2 \right\} \times t dt, \quad (3)$$

$$\eta_{ITAE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} |\Delta F_j| + |\Delta P_{k-m}| \right\} \times t dt, \quad (4)$$

where $\Delta F_j$, and $\Delta P_{tie\ k-m}$ are the deviations in frequency and tie-power with area numbers ($j$, $k$, $m$, $and$ $n$) and time ($t$). ISE, IAE penalizes greater magnitudes errors over smaller ones. Further, ISE, IAE tolerates smaller magnitude errors that persist over long periods. This results in substantially smaller amplitude oscillations with larger settling times. In contrast, ITSE and ITAE consider greater magnitude errors with time. If fewer deviations in error persist over shorter durations, the corresponding errors will be small, and squaring makes it much smaller. If these smaller errors are multiplied by time, they will be much smaller when compared to earlier. So, in this condition, integral time errors will provide better results than integral errors.

During optimization, the conventional PICs consider the area below the curve (ABC), but dint consider the error peak magnitude summation. By considering this, Pathak et al. [214] proposed a new PIC named hybrid peak area (HPA)–PIC: (a) HPA–ISE, (b) HPA–ITSE, (c) HPA–IAE, and (d) HPA–ITSE for optimization and their respective equations are given by (5)–(8) respectively [220].

$$\eta_{HPA-ISE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} (\Delta F_j)^2 + (\Delta P_{k-m})^2 + |\Delta F_{j,\ peak})| + |\Delta P_{k-m,\ peak}| \right\} dt, \quad (5)$$

$$\eta_{IAE} = \int_0^t \left\{ \sum_{\substack{j,\ k\ and\ m=1 \\ k\neq m}}^{n} |\Delta F_j| + |\Delta P_{k-m}| + |\Delta F_{j,\ peak})| + |\Delta P_{k-m,\ peak}| \right\} dt, \quad (6)$$

**Table 4** Performance assessment in a two-area AGC/LFC deregulated system

| References | System description | Operating scenarios | Comparisons | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Controllers | Settling time | | | Peak overshoot | | |
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [70] | Area-1: Thermal Area-2: Thermal | Controller comparison | PI | 16.580 | 11.790 | 8.730 | 0.0206 | 0.0206 | 0.0051 |
| | | | PID | 9.8200 | 6.6700 | 1.7800 | 0.0154 | 0.0117 | 0.0035 |
| | | | FPID | 2.6000 | 3.3400 | 1.4800 | 0.0165 | 0.0128 | 0.0038 |
| | | | FPIDN–FOI | 1.3500 | 2.0400 | 0.7500 | 0.0026 | 0.0110 | 0.0004 |

| References | System description | Operating scenarios | Controllers | Cost value or convergence values (η) | | | |
|---|---|---|---|---|---|---|---|
| | | | | ISE | ITSE | IAE | ITSE |
| | | PIC comparison | PI | 0.2710 | 0.2710 | 0.8070 | 9.8350 |
| | | | FPIDN | 0.0085 | 0.0085 | 0.2649 | 0.6889 |
| | | | FPIDN–FOI | 0.0022 | 0.0022 | 0.1360 | 0.3728 |

| References | System description | Operating scenarios | Comparisons | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Controllers | Settling time | | | Peak overshoot | | |
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [76] | Area-1: Thermal, DSTS Area-2: Thermal, WTS | Controller comparison | I | 60.00 | 62.20 | 75.27 | 0.016 | 0.010 | 0.011 |
| | | | PI | NS | NS | NS | 0.020 | 0.009 | 0.0013 |
| | | | PID | 38.86 | 42.82 | 71.20 | 0.011 | 0.005 | 0.004 |

| References | System description | Operating scenarios | Comparisons | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Controllers | Settling time | | | Peak overshoot | | |
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [140] | Area-1: Thermal, Thermal Area-2: Hydro, Gas | Controller comparison | 2DOF–PI | NS | NS | NS | 0.0758 | NS | 0.0064 |
| | | | 2DOF–PID | 79.000 | 76.234 | 99.990 | 0.0377 | 0.0025 | 0.0015 |
| | | | 2DOF–TID | 49.830 | 52.654 | 54.76 | 0.0802 | 0.7531 | 0.0087 |
| | | AC and HVDC | AC | 49.830 | 42.361 | 54.76 | 0.0802 | 0.0694 | 0.0087 |
| | | | HVDC | 43.910 | 39.451 | 39.56 | 0.0018 | 0.0224 | 0.0013 |

**Table 4** (continued)

| References | System description | Operating scenarios | Controllers | Cost value or convergence values (η) | | |
|---|---|---|---|---|---|---|
| | | | | Poolco | Bilateral | Contract violation |
| [59] | Area-1: GTTP, Thermal, DSTS<br>Area-2: GTTP, Thermal, DSTS | PIC comparison | I | 0.000606 | 0.0004057 | 0.008149 |
| | | | PI | 0.0004893 | 0.0052102 | 0.0068295 |
| | | | PID | 0.0004057 | 0.0050979 | 0.006556 |
| | | | FOPI–FOPID | 0.0001749 | 0.0015696 | 0.001976 |

$$\eta_{ITSE} = \int_{0}^{t} \left\{ \sum_{\substack{j,\ k\ \text{and}\ m=1 \\ k \neq m}}^{n} (\Delta F_j)^2 + (\Delta P_{k-m})^2 + |\Delta \mathrm{F}_{\mathrm{j,\ peak}})| + |\Delta \mathrm{P}_{\mathrm{k\ -\ m,\ peak}}| \right\} \times t dt, \tag{7}$$

$$\eta_{ITAE} = \int_{0}^{t} \left\{ \sum_{\substack{j,\ k\ \text{and}\ m=1 \\ k \neq m}}^{n} |\Delta \mathrm{F_j}| + |\Delta \mathrm{P}_{\mathrm{k\ -\ m}}| + |\Delta \mathrm{F}_{\mathrm{j,\ peak}})| + |\Delta \mathrm{P}_{\mathrm{k\ -\ m,\ peak}}| \right\} \times t dt, \tag{8}$$

where $\Delta F_{j,peak}$ and $\Delta P_{tie\ k\text{-}m\ peak}$ are the magnitude of peak deviations in frequency and tie-power. As a result, the proposed HPA–PICs minimize ABC and peak magnitudes and are tested with the GWO technique. Also, simulations are conducted on the IEEE 39 bus system considering the proposed HPA–PICs with GWO. It is observed that system dynamics with HPA–PICs are superior to conventional PICs.

## 4 Conclusions and Future Scope

### 4.1 Conclusion

A critical review of contemporary ideologies in the AGC field is presented in this work. Recent advancements include development in realistic RES models, modern, advanced, and cascade controller design, the incorporation of virtual inertia and PLL in HVDC systems, modeling of accurate HVDC tie-line system, and the application of HPA–ISE, FACTS, and ESD integration for AGC issue has gained importance. The classification of different AGC/LFC strategies has been paid special attention, and its salient characteristics are emphasized.

The comprehensive history of the evolution of PSs AGC is discussed. The recent advancements in conventional and deregulated AGC/LFC study with the integration of RES are presented. RES like wind, DSTS, solar thermal and realistic models like RDSTS and RPWTS are discussed. Analysis from Tables 3 and 4 suggests that with RES integration system dynamics are improved. The application of various classical and modern control techniques such as intelligent controllers, DOF controllers, cascade controllers, MPCs, and sliding mode controllers are broadly conferred. Also, the benefits and drawbacks of the mentioned secondary controllers are discussed briefly in Table 2. Moreover, the observations from Tables 3, 4, 5, 6, 7, 8 and 9 suggest that with advancement in control strategies, system dynamics get enhanced. Further, the application of soft computing optimization techniques such as traditional, heuristic and meta-heuristic techniques and their benefits and drawbacks are analyzed in Table 10. It is observed that dynamics are improved with meta-heuristic techniques. Furthermore, AGC integrated with HVDC interconnection, FACTS, and ESD units are presented. The studies reveal better

**Table 2** Summary of secondary control techniques with their key benefits and drawbacks [222]

| S. nos, | Control technique | Benefits | Drawbacks |
|---|---|---|---|
| 1. | Classical controller [9, 113, 114] | • Provides quick transient stability<br>• Implementation is easy<br>• Less cost | • Dynamic performance is poor<br>• Not accurate |
| 2. | Intelligent controller [112, 121] | • Natural design<br>• An explicit model is not required<br>• Ideal for small systems<br>• Controllers might be set up through training and the utilization of novel rules<br>• They are completely capable of dealing with systems that have uncertainties and non-linearities | • Utilizes trial and error method<br>• Comprises a large number of tuning parameters<br>• It is primarily helpful in the trained area<br>• Difficulties with the stability analysis<br>• Handling weak limitations |
| 3. | Degree of freedom (DOF) controller [136–138] | • The DOF refers to the number of control loops that can be adjusted and perform control action autonomously<br>• It reduces the difference between reference and measured signals in an effective manner<br>• It enhances the system's stability by eliminating the disturbance occurring in the system<br>• The DOF controller has more number of input signals with weighted values, which shows additional benefits over conventional controllers | • As the control loop number increases, the controllability of the system becomes complicated |
| 4. | Cascade type controller [55–57] | • Two feedback control loop structure<br>• It attenuates the disturbances<br>• Shapes the final output<br>• It has the benefits of combining any kind of controller | • Slow response |
| 5. | Model predictive controller [148–150] | • Constraints can be handled explicitly<br>• It adjusts the current time slot by considering future time slots<br>• It works effectively in a multi-variable system | • It takes a long time for execution<br>• Complex algorithm |
| 6. | Sliding mode controller [158–161] | • It can be used for non-linear controller techniques<br>• Suited for limited-condition systems | • Not considered for the transient response<br>• Large time delay response |

performance over conventional/deregulated units. Studies with performance comparison among various FACTS and ESD show augmented responses with IPFC and RFB. The literature considering realistic RES and accurate HVDC models under conventional and deregulated scenarios is also discussed. Furthermore, the AGC/LFC literature considering conventional PICs and HPA–PICs is briefly presented and is evident that with HPA–ISE AGC system has shown significant improvement in dynamics. The application of AGC in a deregulated/restructured PS and its challenges are overviewed deeply.

## 4.2 Future Scope

Increased load demands and changes in lifestyle tend to have environmental consequences as the population grows. As a result, the modern PS is experiencing structural alterations and heading towards a hybrid PS. In hybrid PS, the inertia levels fall due to RES. So, it is self-evident that the future hybrid PS would encounter frequency regulation issues. Consequently, depending on the application, a contemporary control mechanism with suitable optimization techniques considering FACTS and ESD is required to mitigate the LFC issues. As a result, the AGC study has a promising future.

**Table 3** Performance assessment in a two-area AGC/LFC conventional system

| References | System description | Operating scenarios | Comparisons | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Controllers | Settling time | | | Peak overshoot | | |
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [70] | Area-1: Thermal<br>Area-2: Thermal | Controller comparison | PI | 16.58 | 11.79 | 8.73 | 0.0206 | 0.0206 | 0.0051 |
| | | | PID | 9.82 | 6.67 | 1.78 | 0.0154 | 0.0117 | 0.0035 |
| | | | FPID | 2.60 | 3.34 | 1.48 | 0.0165 | 0.0128 | 0.0038 |
| | | | FPIDN–FOI | 1.35 | 2.04 | 0.75 | 0.0026 | 0.011 | 0.0004 |

| References | System description | Operating scenarios | Controllers | Cost value or convergence values (η) | | | |
|---|---|---|---|---|---|---|---|
| | | | | ISE | ITSE | IAE | ITSE |
| | | PIC comparison | PI | 0.2710 | 0.2710 | 0.8070 | 9.8350 |
| | | | PID | 0.2001 | 0.1470 | 0.5483 | 0.8402 |
| | | | FPIDN | 0.0085 | 0.0085 | 0.2649 | 0.6889 |
| | | | FPIDN–FOI | 0.0022 | 0.0022 | 0.1360 | 0.3728 |

| References | System description | Operating scenarios | Comparisons | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Controllers | Settling time | | | Peak overshoot | | |
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [76] | Area-1: Thermal, DSTS<br>Area-2: Thermal, WTS | Controller comparison | I | 60 | 62.20 | 75.27 | 0.016 | 0.010 | 0.011 |
| | | | PI | NS | NS | NS | 0.020 | 0.009 | 0.0013 |
| | | | PID | 38.86 | 42.82 | 71.20 | 0.011 | 0.005 | 0.004 |

| References | System description | Operating scenarios | Controllers | Overshoot values at different inertia conditions | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | H = 3 | H = 4 | H = 5 | H = 6 | H = 7 |
| [170] | Area-1: Hydro<br>Area-2: Hydro | Controller comparison at various inertia (H) | ID | 0.0383 | 0.02472 | 0.0215 | 0.0202 | 0.01939 |
| | | | PID | 0.0379 | 0.02499 | 0.0195 | 0.0142 | 0.0142 |

**Table 5** Performance assessment in a three-area AGC/LFC conventional system

| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak overshoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [53] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal | Controller comparison | 2DOF–PI | 50.35 | NA | 62.70 | 0.0097 | NA | 0.000 |
| | | | 2DOF–PID | 35.01 | NA | 61.86 | 0.01 | NA | 0.000 |
| | | | 2DOF–IDD | 34.10 | NA | 51.64 | 0.0095 | NA | 0.000 |
| | | FACTS comparison | SSSC | 33.99 | 24.28 | 51.12 | 0.0013 | 0.0007 | 0.0002 |
| | | | TCCS | 33.06 | 34.46 | 51.13 | 0.0019 | 0.0004 | 0.0002 |
| | | | TCPS | 37.70 | 33.36 | 50.97 | 0.0002 | 0.0004 | 0.0000 |
| | | | IPFC | 28.53 | 23.37 | 34.56 | 0.0082 | 0.0121 | 0.0087 |
| [54] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal | Controller comparison | I | 98.81 | 94.27 | 87.34 | 98.81 | 94.27 | 87.340 |
| | | | PI | 98.76 | 88.23 | 87.33 | 0.0097 | 0.0057 | 0.0031 |
| | | | PID | 72.92 | 63.19 | 70.43 | 0.0084 | 0.0051 | 0.0015 |
| | | | FOPID | 0.0028 | 0.000 | 0.000 | 34.50 | 36.19 | 41.12 |
| [55] | Area-1: Thermal, PWTS<br>Area-2: Thermal, PWTS<br>Area-3: Thermal, STTP | Controller comparison | FOPI | 75.00 | 82.00 | 85.00 | 0.0179 | 0.0143 | 0.0002 |
| | | | FOPIDN | 65.00 | 77.00 | 70.00 | 0.0035 | 0.0099 | 0.0001 |
| | | | FOPI–FOPIDN | 51.00 | 41.00 | 60.00 | 0.022 | 0.0173 | 0.00014 |
| | | | FO-FOIDN | 42.00 | 38.00 | 53.00 | 0.0739 | 0.0042 | 0.0000 |
| [79] | Area-1: Thermal, STPP<br>Area-2: Thermal, Thermal<br>Area-3: Thermal, WTS | Controller comparison | PID | 63.130 | 0.0038 | 94.330 | 0.0017 | 0.0038 | 0.0052 |
| | | | TID | 61.400 | 0.0038 | 83.770 | 0.0018 | 0.0038 | 0.0038 |
| | | | I-TD | 22.970 | 0.0014 | 25.250 | 0.0009 | 0.0014 | 0.0034 |

**Table 6** Performance assessment in a three-area AGC/LFC deregulated system

| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak overshoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [69] | Area-1: Thermal, GTPP<br>Area-2: Thermal, STPP<br>Area-3: Thermal, WTS | Controller comparison | I | 19.850 | 65.420 | 62.200 | 0.0014 | 0.0156 | 0.0046 |
| | | | PI | 15.420 | 63.540 | 41.500 | 0.0012 | 0.0143 | 0.0340 |
| | | | PID | 14.400 | 61.250 | 39.550 | 0.0004 | 0.0117 | 0.0032 |
| | | | FOPI–FOPID | 13.830 | 58.110 | 37.750 | 0.0000 | 0.0042 | 0.0026 |

| References | System description | Operating scenarios | PIC | Settling time | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_3$ | $\Delta P_{tie\ 1-2}$ | $\Delta P_{tie\ 1-23}$ | $\Delta P_{tie\ 1-3}$ |
| [221] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal | PIC comparison | IAE | 4.000 | 3.500 | 3.3000 | 5.0000 | 5.0000 | 5.0000 |
| | | | ISE | 4.000 | 6.000 | 6.0000 | 6.0000 | 8.0000 | 5.0000 |
| | | | ITSE | 4.000 | 3.300 | 3.3000 | 5.5000 | 8.0000 | 4.5000 |
| | | | IAE + ISE | 3.500 | 3.000 | 2.5000 | 6.0000 | 5.0000 | 5.000 |
| | | | ISE + ITSE | 4.000 | 3.500 | 3.5000 | 5.000 | 8.5000 | 5.000 |
| | | | IAE + ISE + ITSE | 3.000 | 2.500 | 2.000 | 5.000 | 5.000 | 5.0000 |

| References | System description | Operating scenarios | ESD | Cost value or convergence values (η) with various ESD | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | BES | FES | CES | SMES | UC | RFB |
| [26] | Area-1: Thermal, GTPP<br>Area-2: Thermal, GAS<br>Area-3: Thermal, GAS | ESD comparison | ISE | 0.0042751 | 0.004222 | 0.003127 | 0.002847 | 0.004874 | 0.001142 |

**Table 7** Performance assessment in a four-area AGC/LFC conventional system

| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak overshoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta P_{tie\ 1-2}$ |
| [120] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal<br>Area-4: Thermal | Controller comparison | PI | 16.58 | 11.79 | 8.73 | 0.0206 | 0.0206 | 0.0051 |
| | | | PID | 9.82 | 6.67 | 1.78 | 0.0154 | 0.0117 | 0.0035 |
| | | | FPID | 2.60 | 3.34 | 1.48 | 0.0165 | 0.0128 | 0.0038 |
| | | | FPIDN–FOI | 1.35 | 2.04 | 0.75 | 0.0026 | 0.011 | 0.0004 |

| References | System description | Operating scenarios | PIC with controllers | Cost value or convergence values (η) with various ESD | | | |
|---|---|---|---|---|---|---|---|
| | | | | ISE | ITSE | IAE | ITSE |
| | | PIC comparison | PI | 0.2710 | 0.2710 | 0.8070 | 9.8350 |
| | | | FPIDN | 0.0085 | 0.0085 | 0.2649 | 0.6889 |
| | | | FPIDN–FOI | 0.0022 | 0.0022 | 0.1360 | 0.3728 |

| References | System description | Operating scenarios | Controllers | Peak overshoot | | | Peak undershoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_4$ | $\Delta F_1$ | $\Delta F_2$ | $\Delta F_4$ |
| [182] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal<br>Area-4: Hydro | Controller comparison | PID | 0.00209 | 0.00072 | 0.00680 | 0.00141 | 0.00146 | 0.00970 |
| | | | FOPID | 0.00167 | 0.00052 | 0.00614 | 0.00110 | 0.00164 | 0.00987 |
| | | | Fuzzy PID | 0.00159 | 0.00065 | 0.00524 | 0.00406 | 0.0041 | 0.00665 |
| | | | Fuzzy FOPID | 0.00160 | 0.00254 | 0.00226 | 0.00113 | 0.00111 | 0.00339 |

**Table 8** Performance assessment with FACTS

| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak overshoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | SSSC | TCPS | UPFC | SSSC | TCPS | UPFC |
| [13] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal | SSSC<br>TCPS<br>UPFC | $\Delta F_1$ | 36.12 | 32.26 | 28.89 | 0.006 | 0.004 | 0.003 |
| | | | $\Delta F_2$ | 35.16 | 28.61 | 22.34 | 0.006 | 0.006 | 0.005 |
| | | | $\Delta F_3$ | 30.10 | 29.16 | 25.41 | 0.003 | 0.001 | 0.001 |
| | | | $\Delta P_{tie\ 2\text{–}3}$ | 40.06 | 39.58 | 32.34 | 0.002 | 0.018 | 0.018 |
| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak undershoot | | |
| | | | | SSSC | TCPS | IPFC | SSSC | TCPS | IPFC |
| [53] | Area-1: Thermal<br>Area-2: Thermal<br>Area-3: Thermal | SSSC<br>TCPS<br>IPFC | $\Delta F_1$ | 33.99 | 31.7 | 28.53 | 0.0013 | 0.0007 | 0 |
| | | | $\Delta F_2$ | 24.28 | 33.36 | 23.37 | 0.0019 | 0.0004 | 0 |
| | | | $\Delta P_{tie\ 1\text{–}2}$ | 51.15 | 50.97 | 34.56 | 0.0002 | 0 | 0 |
| | | | $\Delta P_{tie\ 2\text{–}3}$ | 29.12 | 34.32 | 29.12 | 0 | 0 | 0 |

**Table 9** Performance assessment with ESD

| References | System description | Operating scenarios | Comparisons | Settling time | | | Peak overshoot | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $\Delta F_2$ | $\Delta F_3$ | $\Delta P_{tie\ 2\text{–}3}$ | $\Delta F_1$ | $\Delta F_3$ | $\Delta P_{tie\ 2\text{–}3}$ |
| [13] | Area-1: Thermal + GTPP + Hydro<br>Area-2: Thermal + Wind<br>Area-3: Thermal + Solar PV | BES<br>FES<br>CES<br>SMES<br>UC<br>RFB | BES | 18.00 | 19.00 | 22.12 | 0.00015 | 0.0006 | 0.00026 |
| | | | FES | 16.01 | 18.50 | 20.15 | 0.00014 | 0.0055 | 0.00025 |
| | | | CES | 15.81 | 17.01 | 18.54 | 0.00010 | 0.0048 | 0.00024 |
| | | | SMES | 15.11 | 15.12 | 16.45 | 0.00008 | 0.0042 | 0.00022 |
| | | | UC | 14.50 | 13.00 | 14.20 | 0.00006 | 0.0003 | 0.00020 |
| | | | RFB | 13.01 | 10.11 | 13.01 | 0.00003 | 0.0002 | 0.00018 |

**Table 10** Summary of optimization techniques with their key benefits and drawbacks

| S. Nos | Optimization techniques | Benefits | Drawbacks |
|---|---|---|---|
| | Traditional algorithms/numerical methods [223] | • It is a step-wise depiction of a problem<br>• Comprises of own logical sequence<br>• It is easier for a programmer to understand | • Slow convergence<br>• Sticks at local optima<br>• It takes a large number of iterations |
| | Heuristic algorithms [224] | • Solves practical problems<br>• Provides fast responses<br>• Gives feasible solutions | • Not applicable to all practical problems<br>• Lack of flexibility<br>• Unable to deliver global optima solution |
| | Metaheuristic algorithms [55] | • Indeed, it converges to an optimum value<br>• They can handle local and global optimum values<br>• Parameters like intensification and diversification are available | • Low classification accuracy<br>• Low convergence rate<br>• Low precision rate |

**Table 11** Overview of AGC/LFC literature

| | |
|---|---|
| Conventional AGC system | |
| Single-area system | [1–3] |
| Two-area system | [16, 28, 39, 46–50, 76] |
| Three-area system | [13–15, 17, 31, 32, 51–60, 78, 79] |
| Four-area system | [20, 61] |
| Deregulated AGC system | |
| Two-area system | [34, 66, 118, 124, 140, 221] |
| Three-area system | [26, 43, 56, 119] |
| Four-area system | [38] |
| RES integration | |
| Solar–thermal | [32, 47, 57, 78, 79] |
| Solar PV | [70–75] |
| DSTS | [26, 31, 48, 59, 62, 76, 77] |
| Tidal | [67, 68] |
| Wind | [13, 14, 32–34, 39, 62–66] |
| Geo-thermal | [14, 26, 26, 58, 59, 69] |
| PWTS | [55, 85–87] |
| RDSTS | [55, 85–87] |
| Secondary controllers | |
| Integer order controller | [9, 13, 30, 35, 49, 56, 62, 74, 113–118] |
| Fractional order controller | [54–57, 119] |
| Tilt controller | [28, 79] |
| Degree of freedom | [24, 52, 53, 135–142, 162–164] |
| Fuzzy controller | [112, 120–131] |
| Neural networks | [132–134, 136, 137] |
| Cascade controller | [14, 26–28, 40, 47, 48, 57, 59, 69, 78, 143–147, 162] |
| Model predictive controller | [148–152] |
| Sliding mode controller | [156–158] |
| HVDC transmission | |
| HVDC | [15, 31, 59, 120, 175, 196–200, 204, 205] |
| Accurate HVDC | [55–57, 203–205] |
| FACTS device integration | |
| TCPAR | [208] |
| TCSC | [23, 50, 209] |
| SSSC | [19] |
| TCPS | [210] |
| GCSC | [19, 211] |
| SVC | [62] |
| UPFC | [13, 212–214] |
| IPFC | [21, 32–34, 69, 183] |
| ESD integration | |
| Battery storage | [14, 26, 71, 212–215, 217, 218] |
| SMES | [14, 21, 26, 34, 190, 216] |
| CES | [14, 26, 219] |
| UC | [14, 26, 40, 47, 49] |
| Fly wheel | [14, 26, 71, 218] |
| RFB | [14, 26, 37, 48] |

**Table 12** Summary of optimization techniques with various control techniques utilized in AGC/LFC studies

| Optimization technique | Controllers used for the optimization |
|---|---|
| 1 Numerical methods | |
| Differential search algorithm | PIDN [164] |
| Differential evolution (DE) | PID [22]; 2DOF–PID [165] |
| 2 Heuristic techniques | |
| Water cycle algorithm | CC–TI–TD [28] |
| Hill climbing algorithm | FPI [74] |
| Gases Brownian motion optimization | FOPID [172] |
| Quasi opposition-based harmonic search | PID [61, 159]; I [173] |
| Multi-verse optimization | PID–DD [173] |
| 3 Meta-heuristic techniques | |
| Lightning search algorithm | IDDN [30]; PIDN [31]; FOIDN [32]; $PI^{\lambda}DF$ [33]; $PID^{\mu}N$ [34] |
| Yellow saddle goat fish algorithm | PIFOD-(1 + PI) [35] |
| Butterfly optimization | P-FOID [36] |
| Grey wolf optimization (GWO) | Predictive PID [39], PID [167] |
| Firefly algorithm | $I^{\lambda}D^{\mu}$ [54] |
| Crow search | FOPI–FODN [55]; FOPDN–FOPIDN [56]; FOPI–FOIDN [57] |
| Flower pollination algorithm | PI [62] |
| Moth-flame optimization | PI [66] |
| Salp swarm optimization (SWO) | PID [75, 162] |
| Particle swarm optimization (PSO) | PI [72]; I [114] |
| Bird swarm optimization | 2DO1F–TID [140] |
| Bacterial fogging | F-FOPID [16]; I [113, 170]; FOPID [119]; FPI–PID [176] |
| Grasshopper algorithm | Predictive PID [39]; PIDN [35]; I-TD [79]; FPIDN-(1 + PI) [80]; PID [177] |
| Sine–cosine | FOPI–FOPD [26]; FOPI–FOPID [59]; FOI–FOPID [27]; F-I [178] |
| Whale optimization algorithm | 2DOF–PIDN–FOI [40]; PIDN–FOID [48]; IDN–FOPD [78]; IDN–FOPD [145]; PIDN–FOPD [179] |
| Ant lion algorithm | PID + DD [115]; FPID [180] |
| Bio geography based optimization | PID [35, 76];FO–FPID [181]; FO–PI [182] |
| Cuckoo search | 2DOF–PID [53]; PI [183] |
| Imperialist competitive algorithm | FOPI–FOPD [17]; F-FOID [18]; FFOPI–FOPID [70]; PID [117]; F [120]; FFOPI–FOPID [184]; FPIDN-II [185] |
| Genetic algorithm (GA) | PID [71, 77]; FLCS [124]; FPID [186] |
| Teaching learning based | FPID [187] |
| Bat algorithm | MPC [154]; PI [188] |
| Dragon fly | 3DOF–PID [189] |
| Moth swarm algorithm | PID [190] |
| Artificial bee colony | PID [64], FPID [191], adaptive FPID [192] |
| 4 Hybrid algorithms | |
| HALO–PS | $PID^{\mu}$ [15] |
| HSWO–DE | 2DOF–TID [24] |
| HPS–BBO | 3DOF–PID [52] |
| Self-adaptive modified bat algorithm | Fuzzy-PID [170] |
| HTLBO | F-PID [187] |
| HDE–PSO | FPID [193] |
| HGPS | PID [194] |
| HGWO–PSO | 2DOF–PID [195] |
| HBF–PSO | PID [213] |

**Table 13** Summary of ESD with their key benefits and drawbacks

| References | ESD units | Transfer function (G) | Merits | Drawbacks |
|---|---|---|---|---|
| [14, 21, 26, 34, 190, 216] | Super magnetic energy storage (SMES) | $G_{SMES}(s) = \frac{K_{SMES}}{T_{SMES}S + 1}$ <br> $K_{SMES} = 0.12$ *and* $T_{SMES} = 0.03s$ | • Fast response <br> • Time delay is less | • Operational time is less |
| [14, 26, 71, 212–215, 217, 218] | Battery energy system (BES) | $G_{BES}(s) = \frac{K_{BES}}{T_{BES}S + 1}$ <br> $K_{BES} = -0.003$ *and* $T_{BES} = 0.1s$ | • Large density <br> • Fast access time <br> • Can supply bulk power in less time | • Less operational time <br> • It takes more charging time |
| [14, 26, 71, 217, 218] | Flywheel energy storage (FES) | $G_{FES}(s) = \frac{K_{FES}}{T_{FES}S + 1}$ <br> $K_{FES} = -0.01$ *and* $T_{FES} = 0.1s$ | • Reliable <br> • Fast response <br> • Cheaper <br> • Longer life | • Less storage capacity <br> • More losses |
| [14, 26, 219] | Capacitive energy storage (CES) | $G_{CES}(s) = \frac{K_{CES}}{T_{CES}S + 1}$ <br> $K_{CES} = 0.3$ *and* $T_{CES} = 0.0352s$ | • It can be used as a spinning reserve <br> • Fast charging <br> • Fewer losses <br> • Low maintenance | • Low energy capacity |
| [14, 26, 40, 47, 49] | Ultra-capacitor (UC) | $G_{UC}(s) = \frac{K_{UC}}{T_{UC}S + 1}$ <br> $K_{UC} = -0.7$ *and* $T_{UC} = 0.9s$ | • High efficiency <br> • longer life <br> • High power capability | • Low energy density <br> • High cost per installed energy |
| [14, 26, 37, 48] | Redox flow battery (RFB) | $G_{RFB}(s) = \frac{K_{RFB}}{T_{RFB}S + 1}$ <br> $K_{RFB} = 0.9$ *and* $T_{RFB} = 0s$ | • Quick storing action <br> • Quick response <br> • Fewer losses <br> • Can operate at any temperature <br> • Ideal for RES integration | • Expensive fluids <br> • Toxic chemicals |

**Table 14** Capacity and cost analysis of various ESD [14, 26]

| ESD | SMES | BES | FES | CES | UC | RFB |
|---|---|---|---|---|---|---|
| Capacity (MWh) | 10–1000 | 20 | 5 | 0.01 | 0.005 | 6–120 |
| Cost ($/kWh) | > 10,000 | 600 | 2400 | 4600 | 10,000 | 900 |
| Capital cost per cycle ($/MWh/cycles) | 1000 | 150–200 | 25–200 | 10 | 400 | < 70 |

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