Application of HVDC and ESS in Two Area Load Frequency Control System Using PID Controller: A Review

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Abstract
This review examines the application of High Voltage Direct Current and Energy Storage Systems in two area load frequency control frameworks using PID based control strategies. It first outlines the fundamentals of frequency regulation in interconnected power systems, including the role of primary and secondary control, generator load dynamics, tie line power exchange, and area control considerations. The review then discusses the contribution of ESS in balancing intermittent renewable generation and improving transient support in wind diesel and hybrid microgrid operation. In parallel, it explains how HVDC links provide an additional controllable path for inter area power flow and strengthen dynamic regulation. The surveyed literature shows a clear movement from conventional PI and PID control toward optimized PID family, cascaded, fuzzy, and intelligent controllers tuned through metaheuristic techniques. Collectively, the reviewed studies indicate that hybrid support through ESS and HVDC can significantly improve damping, settling behaviour, robustness, and tie line performance in multi area systems.

Keywords: Load Frequency Control, PID Controller, High Voltage Direct Current, Energy Storage System, Two Area Power System, Frequency Regulation.

1. Introduction

The purpose of large power systems with several connected control areas is to have dependable power production and distribution while keeping acceptable characteristics like voltage and frequency [1]. This necessitates balancing the power demand on the load side as well as the power generated. Due to the unpredictability and temporal variability of load demand, variations in frequency and scheduled power exchange are inevitable. This, in turn, impacts a great deal of the power system's operational points. System instability and a subsequent blackout can be the unexpected repercussions of this [2]. “The most typical approach to handling frequency variations is hierarchical control,” which may be separated into primary, secondary, and tertiary levels [3]. To restore harmony to the electrical system, an emergency control loop may be required if the frequency deviates too far from the nominal [4]. “When everything is running well, the main control (time action from many seconds) dampens the little frequency drift. Installing the secondary control loop, also known as an LFC, to restore frequency for more serious deviations (off-normal operation) might take up to 10 minutes, depending on the amount of available conserved power.” It may not be possible to restore the frequency to its nominal via the LFC loop if there is an excessive imbalance between generation and load demand produced by a significant failure. The response will be handled by tertiary control in this instance. To further lessen the likelihood of cascade failures, emergency control services are also used (refer to Figure 1) [5].

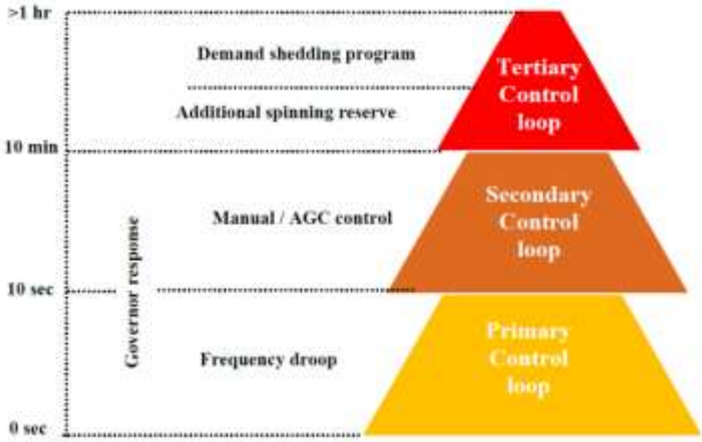


Figure 1: "Frequency control loops in a power system" [6]

A power system's frequency is tied to the actual power balance. The whole system is responsive to changes in frequency, which in turn reflect changes in actual power consumption. Hence, system frequency is a good measuring stick for load imbalance and system generation. Because the kinetic energy of the spinning plant quickly cancels out any short-term energy imbalance, the system frequency changes instantly in response to any disruption. "Extreme frequency excursions beyond the plant's operational range may be caused by a significant loss in generation without an effective system reaction" [7, 8]. "The mechanical power output of the prime mover, which might be a steam turbine, gas turbine, hydro turbine, or diesel engine, determines the actual power provided by a generator." To regulate "the mechanical power of a steam or hydro turbine, one must open and close valves that control the flow of steam or water entering the turbine." Without constant regulation of steam (or water) input to generators to meet actual power demand, "machine speed will fluctuate with frequency change." A power system that operates well has a frequency that is relatively constant [9]. A secondary frequency control loop is standard equipment on most big synchronous generators, in addition to the main one. Figure 2 is a picture of a synchronous generator with frequency control loops installed, illustrated schematically.

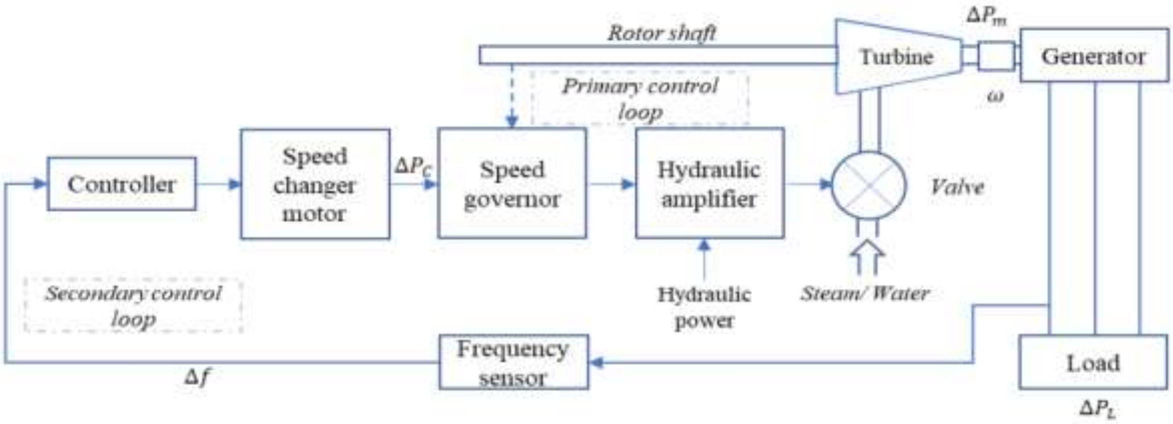


Figure 2: "Schematic block diagram of a synchronous generator with basic frequency control loops" [6].

Figure 2 shows how the speed governor uses the main and secondary control loops to detect changes in speed (frequency). The main valve must be positioned against the high steam (or hydro) pressure, which is provided by the hydraulic amplifier, and the turbine's steady-state power output may be adjusted by the speed changer. No matter where the load change occurs, all of the producing units contribute to the total change in generation via their speed governing, which is primarily controlled by the speed governor on each unit. In most cases, the main control action isn't enough to bring the system frequency back up, particularly in a networked power system, thus the secondary control loop has to be activated to modify the load reference set point via the speed changer motor. The frequency deviation is used by the secondary loop to conduct feedback, which is then added to the main control loop using a dynamic controller. The delta $\boldsymbol{U}\mathbf{O}$ signal is used for frequency regulation of the system. As seen in Figure 2, there is a temporary shift in frequency (Δf) after a change in load (ΔPL). Hence, the feedback mechanism kicks in and produces a suitable signal for the turbine to restore the system frequency, monitor the load, and create generation ($\Delta \boldsymbol{U}u$) [3].

The schematic block design in Figure 2 is depicted with "one generating unit, and this chapter outlines a simplified frequency response model for it." A swing deferential equation may be used "to explain the entire generator-load dynamic connection between the incremental mismatch power ($\Delta Pu - \Delta PL$) and the frequency deviation (Δf)" as specified in [6].

$$\Delta P_m(\mathrm{t}) - \Delta P_L(\mathrm{t}) = 2H_{eq}\frac{d\Delta f(t)}{dt} + D\,\Delta f(t)$$

In this context, "Δf represents the frequency deviation, ΔPu the change in mechanical power, ΔPL the change in load, Hec the constant of inertia, and D is the coefficient of load damping." Typically, the damping coefficient is given as the percentage of load change for a 1% frequency shift. A common value of 1.5 for D indicates, for instance, that a 1% shift in frequency would result in a 1.5% shift in load [3]. "We may rewrite the above equation using the Laplace transform as: $\Delta(y)$ - $\Delta P\mathbf{O}$ (y) equals 2 $\mathbf{b}ec$ s Δf(s) = $D\,\Delta\, f$(s)"

Equation (2.2) can be represented in a block diagram as shown in Figure 3.

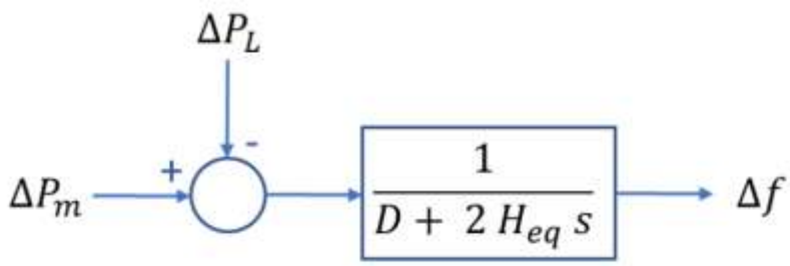
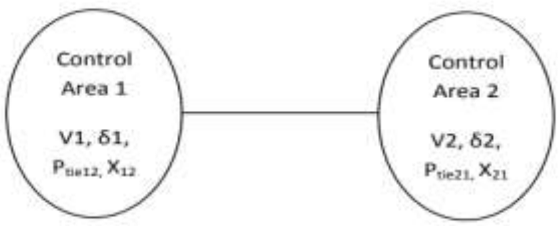


Figure 3: "Block diagram representation of generator-load model" [3].

Keeping the frequency within the nominal limits as the load demand fluctuates is called load frequency control (LFC) [10]. To maintain power balance across linked regions under changing load circumstances, LFC is crucial to power system stability [6, 7]. If the system's load demand is more than or lower than the generator's power, the frequency of the system will become unbalanced. Automatic control actions start load shedding or activate protection relays to disconnect generators in order to maintain the normal frequency [8]. Optimally tuned controllers are crucial for LFC applications because

they effectively stabilize the power system by reducing frequency undershoots, overshoots, and settling time. The popularity and widespread usage of Optimized Proportional Integrative-Derivative (PID) controllers in industry may be attributed to its simplicity and efficiency. Regardless, it seems like a lot of people have been putting a lot of time and effort into designing current controllers. These controllers are often based on fuzzy logic, artificial neural networks, PID, or fractional order. "According to the literature review, a two-area system is managed using a controller that combines a symbiotic organism search algorithm with fuzzy proportional-integral-derivative and proportional-fractional order integral-derivative (PIΛD-FPIśD) [11]." The goal of this study is "to improve the system's stability under loading situations by investigating a fuzzy-based proportional-integral (PI) cascaded controller with sunflower optimization (FPDF+PI) [12]."
For multi-area LFC applications, the salp swarm algorithm (SSA) has been used to optimize a fuzzy PID with a filter controller [13]. "A fuzzy tilt integral derivative (FTID) controller with a filter plus double integral (FTIDF-II) has successfully dampened frequency oscillations [14] using the whale optimization approach." A frequency stabilization controller for different hybrid power systems is presented using "FOPI-PDF (Fractional order proportional integral-proportional derivative with filter) under varying loading circumstances [15]." By modifying the "Grasshopper Optimization Algorithm (GOA) with the Integral Time Absolute Error (ITAE) cost function, a fuzzy-PD-PI controller is created and implemented" in a three-area power system [16]. The suggested controller effectively reduces frequency oscillations with minimal settling time [17] by optimizing "the cascaded PDF and one plus PI (C-PDF(1 + PI)) controller in a microgrid with an ITAE objective function."
New controller designs, optimization methodologies, and hybrid energy storage system integrations have been the focus of recent developments in LFC research. "For a multi-area power system, a quasi-opposition-based equilibrium optimization (QOEO) algorithm is used to tune a fuzzy-based fractional order Proportional Integrative (FFOPI) and PID with filter (PIDN) controller." The results show that this controller has a better settling time response than the PID controller [18]. Several controllers are used in practice to maintain the power system in a regular working condition. When controlling the frequency of a load, the PID controller is used for frequency stabilization [19-21]. Individual load adjustments and planned interchanges with adjoining areas are the responsibility of each control area [22]. Mismatches in frequency and tie line power interchanges, caused by abnormal circumstances and variations in area load, must be kept within acceptable ranges to ensure the power system operates robustly. The effects of the governor dead band are disregarded in the Load Frequency Control studies for the sake of simplicity. Incorporating the governor dead band impact is necessary for studying the realistic analysis of the system performance. An LFC system that regulates active power at tie lines and power production is essential for designing stable power networks.

2. Mathematical modelling of LFC



Voltage is reliant on reactive power limit, and power systems rely on frequency, which in turn depend on active power. There are two distinct issues with the control power system. Load frequency control

(LFC) refers to the regulation of frequency by active power [3-4]. A key function of LFC is to keep the frequency deviation constant in the face of unknown external load disturbances, which may be described as the continuous change of loads. One key responsibility of LFC is power exchange mistake. In order to make a power system fault resistant, it typically comprises of many interconnected generating units that are linked by tie-lines. A new control issue mistake, the tieline power exchange error, is introduced by this utilization of tie-line power. When it comes to linked power systems and error minimization functions, area controller error (ACE) plays a significant role. This work proposes a particle swarm optimization adjusted PID controller and compares its performance to that of traditional PI and PID controllers, as well as the performance of the two-area power system's load frequency regulation.
Transfers of energy from Region 1 to Region 2 are

$$P_{tie12} = \frac{|V1||V2|}{X_{12}} \sin(\delta 1 - \delta 2) \text{ ---------- } (1)$$

There will be a little shift in the power angle if the load needs of two different locations vary. The incremental changes in δ 1 and δ 2, denoted as Δδ1 and Δδ2, respectively, the change in power is

$$P_{tie12} + \Delta P_{tie12} = \frac{|V1||V2|}{X_{12}} \sin[(\delta 1 + \Delta\delta 1) - (\delta 2 + \Delta\delta 2) \text{ -- } (2)$$

$$P_{tie12} = \frac{|V1||V2|}{X_{12}} \cos(\delta 1 - \delta 2)(\Delta\delta 1 - \Delta\delta 2) \text{ ---- } (3)$$

$$T_{12} = \frac{|V1||V2|}{X_{12} * P1} \cos(\delta 1 - \delta 2) \text{ --- } (4)$$

$$\Delta P_{tie12}(p.u) = T_{12}(\Delta\delta 1 - \Delta\delta 2) \text{ --- } (5)$$

$$P_{max12} = \frac{|V1||V2|}{X_{12}} (\Delta\delta_1 - \Delta\delta_2) \text{ ---- } (6)$$

$$T_{12} = \frac{P_{max12}}{P1} \cos(\delta 1 - \delta 2) \text{ --- } (7)$$

$$2\pi\Delta f = \frac{d\delta}{dt} \text{ ----- } (8)$$

Incremental tie line power output of area1

$$\Delta P_{tie12}(P.U) = 2\Pi T_{12}(\frac{\Delta f1}{s} - \frac{\Delta f2}{s}) \text{ -------- } (9)$$

On taking Laplace transform on both side, then

$$\Delta P_{tie21}(s) = \frac{2\Pi T_{12}}{s} (\Delta f2(s) - \Delta f1(s)) \text{ --- } (10)$$

$$T_{21} = a_{12} T_{12} \text{ Then}$$

$$\Delta P_{tie21}(s) = \frac{-2\Pi T_{21}}{s} (\Delta f1(s) - \Delta f2(s)) \text{ --- } (11)$$

The swing equation [5] states that...Assuming that the load at area 1 grows, the power balance is

$$\Delta P_G - \Delta P_D = \frac{2H}{f^0} \frac{d}{dt} \Delta f + B\Delta f \text{ ---- } (12)$$

"Where H- Inertia constant, f0 – Nominal frequency, Δf- change in frequency, B- Area parameter."

3. Energy Storage Systems (ESS) in Two Area Power Systems

In recent decades, academics and corporations have shown significant interest in hybrid microgrid systems (HMS), which combine various micro-renewable sources with energy storage systems (ESS) [23, 24]. Power provided by renewable sources, such as solar and wind, should be considered significant if it exhibits stochastically variable and intermittent characteristics. Power storage devices including supercapacitors, battery energy storage systems, and magnetic energy storage systems are discussed in references [24, 25]. Large and severe power fluctuations may be caused by the unpredictable nature of wind speeds, changes in solar irradiation, and disturbances to the load [25, 26]. The system's frequency and voltage changes might be severely disrupted by the unpredictable power production of these renewable sources. To keep the system's dynamic performance within an acceptable quality tolerance and to stabilise these fluctuations, the load frequency controller's (LFC) primary function is to operate [26, 27]. This highlights the vital need of having suitable and efficient LFCs, especially when the grid is run independently.

"In (Wind-Diesel) WD mode, the Wind Turbine Generators (WTGs) often consume reactive power and also provide it, as Sebastián and Quesada [28] pointed out." In this mode, the frequency and voltage are controlled by the same regulators as in DO mode (see Figure 4). "A Dump Load (DL) is required to dump the power required to prevent power inversion in diesel generators because the outgoing active power from the power plant, P_L-P_T, might be negative." To increase the performance of diesel generators and decrease the demand for spinning reserve, an Energy Storage System (ESS) may be used in both (Diesel-Only) DO and WD modes.

If the power output from the WTG is more than the power used by the load (plus a safety margin), then the WO mode may be activated. "Auxiliary components are required to regulate voltage and frequency in WO mode since the diesel generators are not operational and the active power is supplied only by the wind turbines (I_G=OFF, I_T=ON)." When the reactive power provided by the sources is equal to the reactive power absorbed by the sinks, the voltage is specified by the automated reactive power balance [29]. "When the SM's voltage regulator (I_SM=ON) is turned on, it will regulate the machine's excitation to provide the reactive power needed to attain equilibrium with a voltage V in the common bar equal to the nominal voltage." Controlling the frequency is as simple as keeping the active power consumption and production in perfect harmony at all times. In order to achieve this balance in active power, the Energy Storage Systems (ESS) may either store the excess active power from the wind turbine (P_s>0) or recover it (P_s<0) at times when the wind power is lower than the present load. Additionally, DL can consume the excess wind power (P_D>0), thus we can say:

$$P_T - P_L - P_D - P_S = J\omega\omega' \qquad (1)$$

$$P_D < P_{D\text{-}NOM} \text{ and } P_S < P_{S\text{-}NOM} \qquad (2)$$

ϋ is the speed of the shaft in radians per second, "which is related to the frequency of the voltage waveform f by the formula ω=2πf/p, where p is the number of pairs of poles of the shaft, J is the system's inertia, and P_t and $P_)$ are the active power generated and consumed by the WTG and the load, respectively, when P_+>0." Equation 2 states that P and P_s must be less than the nominal power of their respective converters, but equation 1 does not account for losses. "The synchronized shaft speed, which is the frequency of the voltage waveform, has to be maintained constant (ϋ'=0) by coordinating the DL controller and the ESS controller to discharge only the surplus wind power that cannot be stored, preferably with P_t-P□=Pz+P_s."

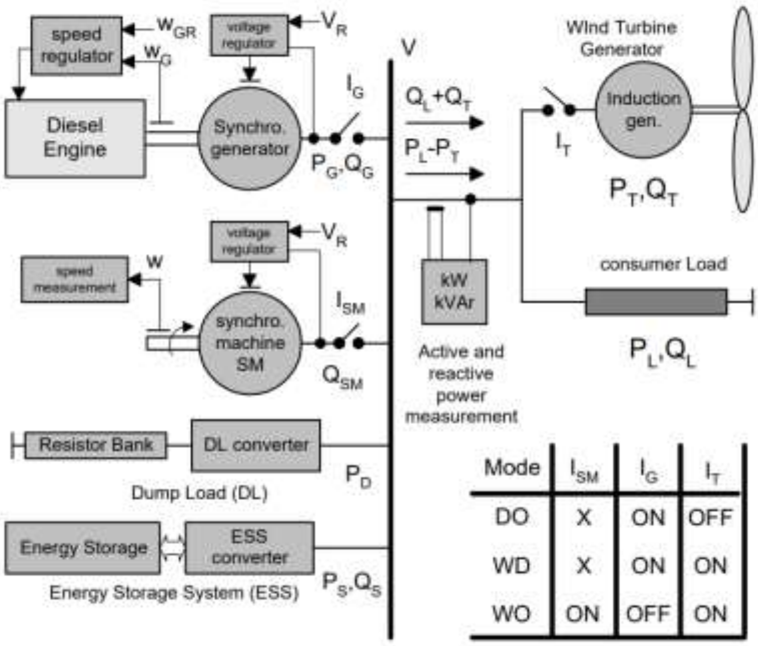


Figure 4: "Wind-Diesel Hybrid System" [28]

4. High-Voltage Direct Current (HVDC) in Two Area Power Systems

Figure 6 shows a two-area power system with a single line structure. In order to regulate the DC-Line power flow, tools like inverters and rectifiers are used as switching devices. The $\Delta Ptie1,2ac$and $\Delta Ptie1,2dc$ power flows via the AC tie-line and the DC tie-line, respectively. Theoretical details of HVDC for LFC may be found in [30-32]. Direct Current—Line The following equation represents the first-order transfer function:

$$\Delta P_{tie,dc} = \frac{K_{DC}}{1+sT_{DC}}$$

"K_{DC} Indicates HVDC model Gain, T_{DC} Time constant of HVDC line."

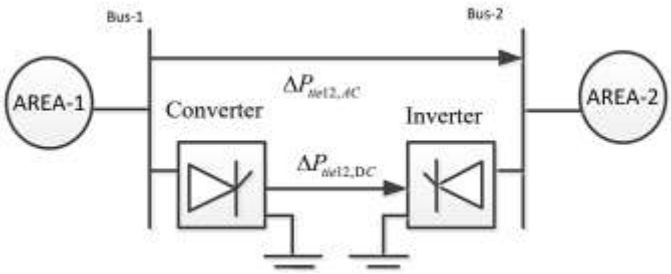


Figure 5: "HVDC Connections with AC Tie-Line" [33]

Figure 6 shows the design of the two-region linked power system that was proposed by Moschos & Parisses [34]. In each control area, there are reheat thermal, hydro, gas, and geothermal producing units. There is 0.06% GDB and 10% GRC every minute in the reheat thermal system. There is a setting of 270%/min for the GRCof rising generation and 360%/min for decreasing generation for the hydro units.

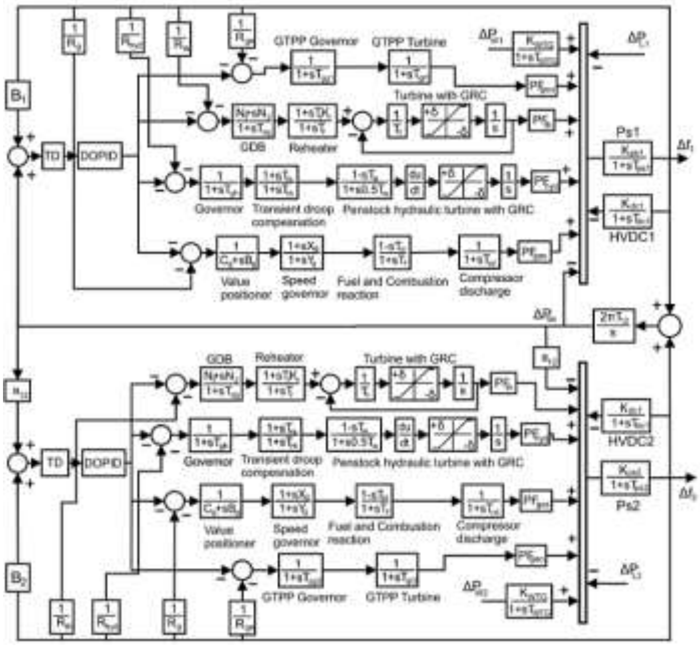


Figure 6: Block diagram of two-area interconnected power system studies in [34].

By taking the ITAE performance index into account, the controller parameters are optimized with 1% SLP in region 1 using the marine predators algorithm:

$$ITAE = \int_{0}^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|)\, t\, dt$$

5. Empirical Review of optimised PID controllers in multi Area Power Systems

An integrated dual-area thermal and solar photovoltaic (PV) power system was investigated by Çelik et al. [35] to determine how an energy storage device (ESD) might improve the LFC performance. A proportional-integral (PI) controller is first used in the system to reduce frequency and tie-line power variations since it is simple to use and effective. The ideal controller settings are sought for utilizing the salp swarm algorithm (SSA) with the integral of time-multiplied absolute error (ITAE) criteria, in order to get the best performance from this controller. A comparison with a more modern method that uses PI controllers optimized by genetic algorithm (GA) and firefly algorithm (FA) is made to validate the value of SSA optimized PI controller.

A two-area linked system that is subject to wave energy disturbance is described in a study by Elsaied et al. [36]. There is no frequency variation while the system is in steady state since the frequency is kept at the nominal value. The tie line power remains constant in steady state as well. However, the system frequency could be affected by changes in the load in any of the two sectors. The frequency deviation may also be impacted by variations in renewable energy. This article explains how to improve system stability during load changes by using the first two controllers. Both PID and PIDA controllers, which stand for proportional-integral-derivative and acceleration, serve this purpose. In order to fine-tune the settings of the controllers, this article presents three optimization strategies. Three optimization methods are available: the sine-cosine algorithm (SCA), the harmony search algorithm (HS), and teaching-learning-based optimization (TLBO). The two methods that performed the best throughout the trial were PIDA and TLBO. When coupled with PIDA and the TLBO approach, the system is then perturbed by a wave energy conversion system (WECS).

In their study, Sharma and Singh [37] used a two-area power system with multi-generating units to implement virtual inertia (VI) regulation using a PID controller based on particle swarm optimization (PSO). The reaction time and frequency fluctuation are both enhanced by this. In order to simulate the VI, which regulates the active power of the energy storage device that supplies the power system with inertia support, this research employs a derivative control approach. One measure of PSO's efficacy is the integral time absolute error, or ITAE. Integrating electric cars as vehicle-to-grid resources augments the main frequency control. As a last step, we compared the VI with PSO-PID control to the traditional control (PI) and looked at a number of disturbance scenarios. Applying MATLAB/Simulink, the simulation shows that the VI with PSO-PID outperforms a conventional controller by improving settling by 45.84% in Area 1 and 39.77% in Area 2, both with about the same overshoot of frequency deviation.

Ojha and Maddela [38] fine-tuned the PID and cascaded PI-PDN controllers for LFC of the renewable integrated two-area power system using the brown bear optimization algorithm (BOA). For the PID controller to achieve its optimum gains, the ITAE objective function is used. On a RES integrated two-area power system, under different conditions, the performance of LFC with BOA-tuned PID controller is compared to that of other optimization approaches, namely GWO and PSO. Additionally, by contrasting the PID and cascaded PI-PDN controllers' performance, the BOA's efficacy is confirmed. When compared to the GWO and PSO methods, BOA provides better performance, according to the simulation data.

Within the context of the LFC issue of a multi-area multi-source deregulated power system (MAMS-DPS), Kumar and Prasad [39] provide an examination of the efficiency of the charging and discharging process of electric vehicles (EVs) as a sink or a DES. Electric vehicles' ability to store and retrieve energy has a significant influence in reducing the frequency of DPS deviations. Here, we take a look at the AGC system issue in a two-area DPS with two non-reheat thermal power sources and an aggregated fleet of EVs in each area. In the reconfigured DPS environment, a contract participation matrix called the DPM specifies the electric power contract between distribution (DISCOs) and generating (GENCOs) businesses. As a result of changes in load, the produced and tie-line powers, as well as the frequency of area deviation, vary in DPS. In order to address these issues, we compared the performance of control schemes based on the optimization algorithms of GA, PSO, PI, and PID with that of TLBO, which we use to access the effectiveness of electric vehicles.

In their study, Kumar et al. [40] demonstrate how to optimize the Proportional Integral and Derivative (PID) controller in a two-area hybrid power system to keep the frequency and tie-line power constant. With the integral time multiple absolute error (ITAE) as the goal function, the settings of the proportional-integral-derivative (PID) controller were determined using the Gravitational Search Algorithm (GSA). A hybrid power system combines many power sources, including wind turbines, photovoltaic panels, a diesel engine generator, and an energy storage device.

The goal of the work of Saravanan et al. [41] was to improve the management of power systems, make them more stable and responsive to changing circumstances, and provide new knowledge to the area. In this case, think about the two-area system that uses generating plants such as thermal, hydro, gas, distributed generation (solar, wind turbines), and so on. The suggested approach sidesteps less dynamic but speedier disruptions. To further enhance the intended controller settings, the RSA-HBA methodology is used, which combines the reptile search algorithm with the honey badger algorithm. When simulating the network, a high-voltage DC tie line is also used. The MATLAB program is used to implement the suggested strategy and compare it to current techniques. The suggested method

outperforms the alternative salp swarm optimization (SSA), SOA, and FFA methods that are already in use. The electric car technology reduces frequency fluctuation and tie-line power variation, measuring −0.0019 MW, according to the simulation.
The AGC design of multi-area systems that incorporate various inputs was discussed by Meseret and Saikia [42]. The thermal units, solar PV, and wind farm make up Area 1. Solar electricity, hydroelectric dams, and wind turbines are all part of Areas 2 and 3. Optimizing the gains and other parameters of secondary controllers is done using a skill optimization algorithm (SOA). After comparing the many useful performance indices, such as ITSE, ISE, ITAE, and IAE, the ISE was determined to be the most effective. In comparison to PDF-PIDF and PIDF, the suggested cascaded NF-PDF-PIDF controller achieves better dynamic performance for the system. Additionally, it is discovered that dynamic responses may be achieved by combining solar PV with energy storage systems, such as SMES. Additionally, the effects of integrating HVDC and AC tie-lines on the reaction time of the system are investigated. We find that the dynamics provided by parallel AC-HVDC tie-lines are superior to those of AC tie-lines alone. Lastly, a wide-ranging modification to the system's loading has been implemented, using the robustness of the SOA-optimized suggested cascaded (CNF-PDF-PIDF).
In their study, Wang and Nguyen Thi [43] detail the outcomes of a multi-machine system that receives power from an offshore wind farm (OWF) via a high-voltage direct-current (HVDC) connection that is based on a line-commutated converter (LCC). The investigated system may have its damping improved with the help of a well-designed ANFIS damping controller installed at the HVDC link's inverter station. A modal-control designed PID damping controller and the suggested ANFIS control system are compared using a frequency-domain approach based on the eigenvalue and root-loci technique. The efficiency of the suggested control strategy is also examined using a time-domain scheme that is based on a nonlinear system model that is susceptible to a three-phase short-circuit failure. While both damping controllers can provide sufficient damping to the studied system's dominant modes, the designed Adaptive-network-based fuzzy inference system (ANFIS) damping controller greatly improves the system's stability when subjected to a severe disturbance, according to the results of the comparative simulations.
A deregulated realistic interconnected power system that uses an inertia emulation controlled (INEC) HVDC tie-line was developed by Murali & Shankar [44]. The method involves load frequency control (LFC). Nonlinearities, such as rating limitations of generating systems, dead bands of governor systems, and dynamics of boilers, have been included into the development of the realistic power system scenario. For the secondary level of LFC scheme control, a Proportional-Integral-Derivative controller with a derivative filter (PIDN) is used. The gains of this controller are improved using the Volleyball Premier League (VPL) optimization approach.

Table 1: Summary of the Previous Literature

Ref.	Author(s)	System/Study Context	Controller/Technique Used	Optimization / Evaluation Method	Key Findings
[35]	Çelik et al.	Integrated dual area thermal and solar PV power system with energy	PI controller	SSA optimized using ITAE; compared with GA and FA optimized PI	SSA optimized PI improved frequency and tie line performance and validated the

		storage device support for LFC			usefulness of storage support in interconnected LFC
[36]	Elsaied et al.	Two area interconnected system under wave energy disturbance	PID and PIDA controllers	SCA, HS, and TLBO used for tuning	PIDA tuned with TLBO gave the best transient performance and enhanced system stability under load changes and renewable disturbance
[37]	Sharma and Singh	Two area power system with multi generating units and electric vehicles	PSO based PID with virtual inertia regulation	ITAE based tuning in MATLAB/Simulink	VI with PSO PID improved settling by 45.84% in Area 1 and 39.77% in Area 2 compared with conventional PI, with nearly similar overshoot
[38]	Ojha and Maddela	Renewable integrated two area power system	PID and cascaded PI PDN controllers	BOA using ITAE; compared with GWO and PSO	BOA tuned PID and cascaded controller performed better than GWO and PSO based alternatives
[39]	Kumar and Prasad	Multi area multi source deregulated power system with electric vehicles in each area	PI and PID based LFC schemes	Compared TLBO with GA and PSO	EV charging and discharging significantly reduced frequency deviations and improved AGC performance in deregulated systems
[40]	Kumar et al.	Two area hybrid power system with	PID controller	GSA using ITAE	GSA optimized PID effectively maintained

		wind, PV, diesel engine generator, and ESS			frequency and tie line power in the hybrid two area system
[41]	Saravanan et al.	Two area power system with thermal, hydro, gas, solar, and wind generation; HVDC tie line included	Hybrid RSA HBA based control approach	Compared with SSA, SOA, and FFA in MATLAB	Proposed method gave better performance than existing methods and reduced tie line power variation to very low value
[42]	Meseret and Saikia	Multi area AGC with thermal, solar PV, wind, and hydro inputs across three areas	Cascaded CNF PDF PIDF controller	SOA; compared performance indices ITSE, ISE, ITAE, and IAE	ISE was most effective; proposed cascaded controller outperformed PDF PIDF and PIDF; parallel AC HVDC tie lines gave better dynamics than AC tie lines alone; SMES further improved response
[43]	Wang and Nguyen Thi	Multi machine system receiving offshore wind power through LCC based HVDC link	ANFIS damping controller and PID damping controller	Eigenvalue and root loci based frequency domain analysis; nonlinear time domain validation under severe fault	Both controllers improved damping, but ANFIS performed better than PID under severe disturbance and significantly enhanced stability
[44]	Murali and Shankar	Deregulated realistic interconnected power system with inertia	PIDN controller	VPL optimization	PIDN gains optimized by VPL improved secondary LFC performance in a

		emulation controlled HVDC tie line			realistic system including nonlinearities such as boiler dynamics, dead band, and generation rate limits

6. Conclusion

This review highlights that load frequency control remains a central requirement for the secure operation of interconnected power systems, especially under variable load demand, renewable penetration, and inter area power exchange conditions. The examined literature shows that conventional PID based control continues to be important because of its simplicity and practical relevance, but its performance is increasingly enhanced through intelligent tuning methods, cascaded structures, derivative filters, and hybrid control schemes. The review also makes clear that Energy Storage Systems and HVDC links are not merely supplementary additions but important dynamic support mechanisms. ESS improves frequency regulation by absorbing or supplying active power during disturbances, while HVDC strengthens controllable tie line exchange and damping performance. Across the surveyed studies, optimized PID family controllers combined with hybrid support devices consistently achieve lower frequency deviations, faster settling, and better robustness than conventional approaches. Taken together, the reviewed evidence suggests that future LFC design in two area systems should move toward integrated architectures that combine PID based control, advanced optimization, renewable compatible storage, and AC HVDC coordination for improved stability and operational flexibility.

7. References

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