

Load Frequency and Voltage Regulation in Renewable-Dominated Multi-Source Dual-Area Power System Using Gradient-Based Optimization

Kashif Ali Soomro

Department of Electrical Engineering
Quaid-e- Awam University of Engineering
Science and Technology Nawabshah, Pakistan
Email: alik85009@gmail.com

Imran Ali Bhand

Department of Mechatronic Engineering,
Mehran University of Engineering and
Technology, Jamshoro Pakistan
Email: ali.imran@admin.muet.edu.pk

Ali Hassan

Department of Electrical Engineering
Quaid-e- Awam University of Engineering
Science and Technology Nawabshah, Pakistan
Email: a.hasan11mpe16@gmail.com

Ashar Mumtaz

Department of Mechanical Engineering,
Isra University, Hyderabad
Email: asharpathan01@gmail.com

Moula Bux Kanhio

Institute of Mathematics and Computer
Science, University of Sindh, Jamshoro, Pakistan
Email: mbkanhio@gmail.com

ABSTRACT

The fast growth of residential and industrial demands, combined with the incorporation of renewable energy sources (RESs) like wind and solar, is placing an increasing amount of strain on modern interconnected power systems (IPSs). System stability and dependability may be jeopardized by these additions since they cause notable variations in tie-line power, terminal voltage, and system frequency. Loops for automatic voltage regulation (AVR) and load frequency control (LFC) are essential for delivering high-quality electricity with the least amount of variance. For improved dynamic regulation in a two-area IPS, where one area is fueled by a

traditional thermal generator and the other combines photovoltaic (PV) and wind energy sources, this research proposes a proportional integral derivative (PID) controller. Both domains incorporate battery energy storage systems (BESS) to facilitate frequency regulation. This work's unique contribution is the combination of a perturb and observe (P&O) MPPT-controlled permanent magnet synchronous generator (PMSG)-based wind energy system and a fuzzy-based maximum power point tracking (MPPT) PV system with BESS. A gradient-based optimizer (GBO), a meta-heuristic technique, is used to optimize the PID controller. The fitness function for assessing performance is the integral of time times the squared error (ITSE). A 5% step load perturbation (SLP) is used to compare the frequency, voltage, and tie-line power responses of the GBO-tuned PID controller to those of other GBO-based variants, such as integral–proportional–derivative (GBO-IPD), tilt integral derivative (GBO-TID), and integral–proportional (GBO-I-P) controllers. The suggested GBO-PID controller performs better in this hybrid power system setup, according to extensive simulations. The robustness and efficacy of the suggested controller are further confirmed by sensitivity analysis conducted under varied load fluctuations and parameter adjustments of $\pm 25\%$. Findings show that the GBO-PID controller is a viable option for contemporary, RES-integrated power networks since it consistently stabilizes frequency, voltage, and tie-line power variations with quicker settling times.

Keywords: Dual-area power network; GBO; PID controller; LFC; AVR; ITSE.

Introduction

The expansion of various RESs and smart grid technologies is causing a rapid transition of modern power networks. Controlling the output power so that the frequency deviation, terminal voltage deviation, and interchange power between areas are all zero is the most important control goal in power systems. In an IPS, the AVR and LFC methods are in charge of producing and supplying steady, dependable power while maintaining acceptable levels of voltage and frequency. In a power system, the load is always changing and dynamic. The frequency and voltage of the system change in an incredibly unfavorable way due to the imbalance between generation and load demand. The frequency deviation is managed by modifying the active power demand via the LFC control loop's speed governor action. By modifying the reactive power requirement through the generator excitation of the AVR loop, the terminal voltage deviation is controlled. Designing a clever and reliable control strategy that can effectively reduce terminal voltage and system frequency fluctuations by managing tie-line power flow is an extremely difficult task. For an IPS to be controlled optimally, a controller with an exact tuning scheme must be designed. This study attempts to use a nature-inspired computation-based control technique to effectively control the LFC and AVR systems in a dual area tie-line IPS[1-5].

In recent years, the AVR and LFC controllers have become increasingly crucial to the efficient running of sophisticated and contemporary power networks. For instance, In [1] suggested PI-PD controllers for a multi-area intrusion prevention system based on LPBO, AOA, and MPSO. Tests of the responses of the suggested PI-PD-based control schemes and the current NLTA-PID-based control schemes revealed that the suggested technique outperformed conventional controllers by a large margin[6]. In

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[7] employed a conventional Ziegler-Nichols (ZN) approach and a PID controller adjusted with simulated annealing (SA) to stabilize the two-area IPS. They were successful in regulating both the terminal voltage and the load frequency. To enhance responsiveness,[8] examined the hybrid NN-FTF controller for single-area power system voltage and frequency stability. In [9] suggested FLC and PID controllers based on ZN for a single-area, single-source intrusion prevention system. It was found that the dynamic responsiveness of the system is improved in terms of settling time, oscillation damping, and peak overshoots. Two-area nonlinear IPS's FOPID controller was examined by [10]. MFO was used to determine the FOPID controller's ideal parameters. In [11] suggested an FA-based PID controller for a four-source, two-area IPS that includes non-reheat thermal and hydro generating units. They effectively stabilized the power system while achieving perfect transients. For single-area nonlinear IPS, the IPSO-based CPSS controller was suggested by [12]. Hydro, thermal reheat, and gas generation facilities are all included in their power system model. In [13] a two-area IPS using a PID control technique based on DE-AEFA when nonlinearities like GRC are present. The IPFC, RFBs, and HVDC link were also added to the power system to accomplish notable gains. In [14] proposed SCA-based PI and PIDF controllers with non-reheat and thermal reheat generation units for AVR and LFC loops, respectively. Further enhancements in the system's response were guaranteed by the combined use of a redox flow battery (RFB) and unified power flow controller (UPFC). In [15] created a two-area linear IPS PID controller. With NLTA, PID was successfully optimized. In [16] proposed a PIDD controller for a two-area nonlinear IPS based on GWO. UPFC and SMES were also considered in the design. In [17] examined a two-area, four-source IPS with nonlinearities, such as GDB, TD, and GRC, using a PID controller tuned using FA. In [18] employed a PIDA controller for a single-area, single-source IPS that was tuned with hFPA. The combination of FPA and PFA has been studied to enhance system performance and offer the finest solution worldwide. Researchers have proposed an HHO-tuned TIDF controller for a three-area, two-sources nonlinear IPS[19]. In [20] examined the ADRC controller for a three-area IPS that is based on a second-order error-driven control rule. Wind, geothermal, solar, and electric vehicles are the sources of power for this system. Additionally recommended was a 2DOFI-TDF controller based on HHO that included dish Stirling, wind, sun, and reheat thermal production units [21] for two-source, three-area nonlinear IPS. It was demonstrated that the proposed controller's reaction was better than that of TID, TIDF, and I-TDF. In [22] examined a fuzzy PID based on HAEFA for a two-area, three-source IPS that comprised energy storage devices including UCs, SMES, and RFBs. Based on modeling results, it is possible to successfully integrate ESDs into the LFC-AVR system, and RFBs are better at reducing voltage and frequency oscillations.

For the best control of the LFC loop up to a two area IPS, nature-inspired computation algorithms like the fitness dependent optimizer (FDO), improved fitness dependent optimizer (I-FDO), and hybrid sine cosine algorithm with FDO (hSC-FDO) have been investigated using various controllers like FO-ITD, FO-ITDN, FO-I-PD, I-PD, etc. [23-28]. Additionally, various control schemes have been put out for the AVR loop's individual control [29-33]. In order to address various engineering challenges, researchers have recently proposed a number of computation algorithms inspired by

nature [34-41]. The individual and combined control of AVR and LFC systems in multi-area power networks has been the subject of numerous research studies. Because of the intricate dynamics involved in IPSs, comparatively few studies concentrate on the combined operation of the LFC and AVR loops, even though a sizable amount of the literature discusses these loops separately. Furthermore, to the best of our knowledge, no comprehensive investigation has yet been conducted on a two-area tie-line IPS that combines a variety of conventional and renewable power sources, including thermal, PV, wind, and BESS. This study's motivation stems from this research gap and examines the combined AVR-LFC performance of a dual-area tie-line IPS, where one part is supplied by a traditional thermal generator and the other combines wind and photovoltaic (PV) energy sources. BESS are incorporated into both locations to facilitate frequency adjustment. To optimize the suggested PID controller and its variations, such as I-PD, TID, and I-P controllers, a GBO, a potent meta-heuristic method, is utilized. By adding a new controller optimization approach and system configuration to the body of current research, this study improves the stability and robustness of contemporary renewable-integrated power systems.

For the proposed system, which consists of a thermal two-area tie-line IPS and a one-area multi-source power network that includes solar, wind, thermal, and BESS, mathematical modeling of AVR and LFC loops has been developed in order to achieve coordinated voltage and frequency regulation under dynamic operating conditions. The main contributions of this work are:

Combined AVR-LFC loops for a two-area IPS are mathematically modeled. One area is powered by a traditional thermal generator, while the other integrates BESS, PV, and wind energy sources and is connected by a tie-line.

The PID controller's mathematical modeling using the suggested power networks.

The GBO-based fitness function formulas for the PID controller's ideal tuning.

In order to improve frequency stability, the droop control approach and the BESS's SOC management in [42] is applied, which is coordinated with generator operation, effectively handling large disturbances in uncertain electrical power systems.

In order to assess the effectiveness of the suggested control methodology, a thorough comparison was conducted between GBO-PID and other controllers, including GBO-I-PD, GBO-TID, and GBO-I-P, in a thermal two-area tie-line IPS and a one-area multi-source power network.

By doing a sensitivity analysis and varying the characteristics of a proposed power networks over a range of around 25%, the robustness of the recommended GBO-PID control system was confirmed.

This research study is organized as follows: Section 2 describes the power system; Section 3 discusses proposed control strategies; Section 4 explains the proposed GBO algorithm; Section 5 shows the simulation work and discussions with all necessary data; and Section 6 offers conclusions and future-oriented recommendations.

Modeling of the Proposed Power Architecture

Following section describes the mathematical formulation of the proposed power configuration [3].

Thermal Power Elements

Key elements of thermal power consist of governor, turbine, and load. Each of these components is essential for system's functioning and stability.

Governor: Governor is a mechanical device used to monitor and regulate an engine's speed. Its main purpose is to regulate the engine's average speed when load fluctuates. The block diagram of velocity governor for a power network is illustrated in Figure 1. In this figure, governor's time T_G , and speed governing mechanism is revealed with an unstable fall correction $G_c(s)$. Other parameters include mechanical generator opening time T_M , duty ratio D , droop gain R , turbine time T_r , vary in frequency Δf , alteration in generator power output ΔP , turbine's mechanical power output change ΔP_m , and power load change ΔP_L .

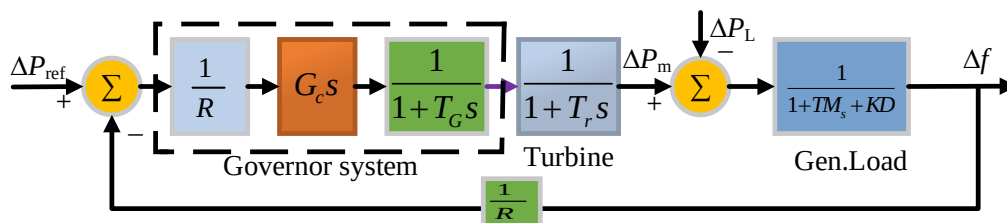


Figure 1. Speed governor illustration.

Turbine: Turbine is a rotational device that generates useful work by transforming energy from the movement of a liquid, like steam, water, or air, into rotational motion. Figure 2 represents transfer function model of turbine. The time delay between valve's switching position and torque of turbine is indicated by T_{ch} .

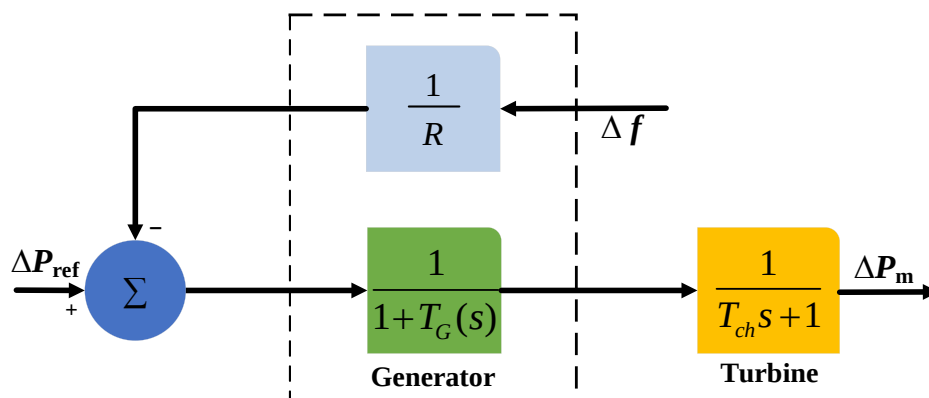


Figure 2. Turbine transfer function illustration.

Load: Power grid encounters different load types. Figure 3 depicts load model, while H stands for generator inertia coefficient, and ΔP_e represents modification in electrical power.

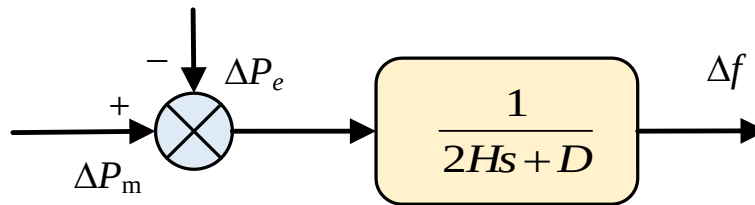


Figure 3. Load model illustration.

$$\text{Governor} = \frac{1}{1 + sT_{sg}} \quad (1)$$

$$\text{Reheater} = \frac{1 + sK_r T_r}{1 + sT_r} \quad (2)$$

$$\text{Steam generator} = \frac{1}{1 + sT_t} \quad (3)$$

Time coefficients for steam turbine, reheater, and governor are indicated, T_{sg} , T_r , & T_t . Figure 4 illustrates, demonstration of a one-area thermal power.

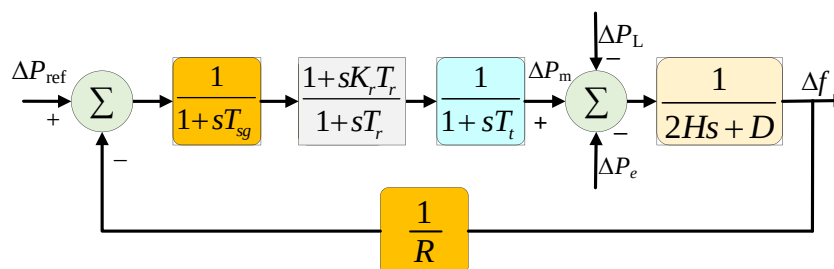


Figure 4. Representation of one-area thermal energy network.

Governor, turbine, and load elements are linked together to create thermal power network. Governor regulates the mechanical power output of turbine ΔP_m in reaction to variations in frequency Δf and load ΔP_L . The turbine subsequently transforms this machine-driven energy into electrical energy, which is fed to grid. Load element illustrates the fluctuations in electrical power consumption, affecting overall constancy and efficiency of power system.

Numerical Modeling of Wind Power Network

The following is an explanation of the wind power system demonstration:

Wind speed modelling:

Wind energy system plays a vital role in determining the electricity generation potential. Under optimal conditions, power that wind turbines can extract is proportional to cube of wind velocity. Kinetic energy given as:

$$E = \frac{1}{2}mv^2 \quad (4)$$

Where m shows moving mass of air and v motion speed. At that time, wind speed reports as:

$$P_{wind} = \frac{E}{\Delta t} \quad (5)$$

Generally, a scalar purpose that evolves to depict wind velocity V , it can also be separated into two distinct elements, which illustrate changes in wind, with one portion that changes gradually, indicated as V_0 , and a component that changes unpredictably, referred to as V_t . Following, wind velocity can be communicated as:

$$V = V_0 + V_t \quad (6)$$

Previous work presents three approaches for mathematically demonstrating wind velocity profile:

Initial method involves a white noise straining system that employs a low-pass filter with a subsequent transferal purpose to mitigate the effects of commotion:

$$F(s) = \frac{1}{1 + \tau.s} \quad (7)$$

While τ is time constant that depends on average wind speed, rotor diameter, and level of wind turbulence.

2nd method for generating a wind velocity profile employs established spectral density by meteorologist I. Van der Hoven to describe variations in wind velocity. Consequently, wind velocity fluctuation V represented:

$$V_v = A + \sum_{i=1}^n \alpha_k . \sin \times \omega_k . t \quad (8)$$

In wind outline scheming, final harmonic rank is represented by i , while α_k denotes largeness of K-order modulation, ω_k indicates vibration of K-order intonation, and A refers to usual wind speed.

3rd method involves Weibull dissemination, which assesses regular wind velocity over specific time intervals to evaluate wind potential at a particular location. Subsequently, a histogram organizes the collected data into numerical values based on classifications of wind speed. Taking into account the specified time and Weibull probability distribution, wind profile can be represented:

$$V_v = (1 + \xi_v - \xi_v).V_v \quad (9)$$

ξ_v mean value of disturbance and V_v mean wind velocity:

$$\xi_v = \left(-\frac{\ln(rand)}{C_v}\right)^{\frac{1}{k_v}} \quad (10)$$

In context of analyzing wind class histograms, (C_v, k_v) represents a pair of parameters. Additionally, *rand* is a expression that produces arbitrary values uniformly between 0 and 1.

Modelling of wind turbine:

Wind power stands as a key nontraditional foundation of energy. It operates through a wind power system, where the capability of wind turbine generator (WTG) is integrated with current energy grid[43]. Vibrant model for WTG is outlined below:

$$\Delta P_{WTG} = \frac{1}{T_{WTG}} \Delta P_w - \frac{1}{T_{WTG}} \Delta P_{WTG} \quad (11)$$

P_w represents wind power, T_{WTG} refers to WTG time continual, and ΔP_{WTG} indicates change in output power of WTG. Rotor of turbine, outfitted with vanes, converts wind energy into mechanical power. Subsequent equations can be employed to mathematically describe wind power harnessed by rotor[44]:

$$P_{rotor} = \frac{1}{2} \rho A V^3 C_p \quad (12)$$

In this context, A represents swept area, V refers to wind velocity, C_p denotes power constant, and ρ signifies wind compactness. Connection among input wind speed and active power is illustrated as follows:

$$P_{GW} = \frac{\rho a^2 V_\omega^3 C_p}{2} (T_{SR}, \beta) \quad (13)$$

β shows pitch angle, T_{SR} tip speed ratio, α area density, V_ω wind velocity. Rotor efficiency C_p :

$$C_p = \frac{T_{SR} - 0.022\beta^2 - 5.6}{2} e^{-0.17T_{SR}} \quad (14)$$

$$T_{SR} = \frac{r_{pm} \pi D}{60V}$$

Turbine produced torque given as:

$$T_t = \frac{P_{GW}}{\omega t} \quad (15)$$

While ωt represents angular velocity of wind turbine rotor.

Gearbox Modelling:

Mechanical components of a wind turbine consist of turbine spindle, turns slowly at a pace of Ω_t , gear assembly that features increase in G , enabling it to drive generator at a faster speed of Ω_g via a secondary spindle.

Utilizing gear assembly, rotor speed Ω_t could be enhanced via multiplication gain G to synchronize with generator's high velocity Ω_g . Deformation, resistance, and energy dissipation associated with gear assembly are considered negligible, which enhances efficiency of this device. Succeeding two equations illustrate the calculated model governing operation of this equipment:

$$\begin{aligned} T_g &= \frac{T_{aer}}{G} \\ \Omega_t &= \frac{\Omega_g}{G} \end{aligned} \quad (16)$$

In case of T_{aer} wind turbine, aerodynamic torque is indicated by Ω_g , speed of generator shaft is represented as Ω_g , and T_g refers to torque on generator shaft. Multiplication gain, denoted as G and Ω_t turbine velocity spindle. Inertia J , which can be articulated by following equation:

$$J = \frac{J_t}{G^2} + J_g \quad (17)$$

Constant of friction for generator f_g and constant of friction for turbine f_t constitute total viscous friction constant f_v , given as:

$$f_v = \frac{f_t}{G^2} + f_g \quad (18)$$

Net mechanical torque T_{mec} , Controls generator's rotational speed Ω_g . This torque represents total of all torques acting on generator shaft T_g (generator torque), T_v (viscous friction torque), and T_{em} (generator's electromagnetic torque).

$$T_{mec} = J \times \frac{d\Omega_g}{dt} \quad (19)$$

$$T_{mec} = T_g - T_{em} - T_v \quad (20)$$

$$T_v = f \times \Omega_g \quad (21)$$

As a result, the following expresses the differential equation governing the dynamics of a mechanical network:

$$J \times \frac{d\Omega_g}{dt} = T_g - T_{em} - T_v \quad (22)$$

This paper concentrates on the output generation of a Wind-powered turbine, particularly utilizing a Permanent Magnet Synchronous Generator (PMSG). Figure 5 depicts schematic diagram of the PMSG wind generator that uses P & O MPPT. Control system for wind generator incorporating PMSG has been created in MATLAB/Simulink. In Figure 8 V_ω , β , T , ω and D represents the angular velocity,

pitch angle, torque generator rotation and duty cycle. The equations below mathematically illustrate the PMSG wind turbine [45, 46].

$$\frac{dw_{gen}}{dt} = \frac{1}{2H_{gen}} \left[-\frac{P_{elec}}{w_{gen} + w_0} - D_{tg}(w_{gen} - w_{rot}) - k_{tg}\Delta\theta_m \right] \quad (23)$$

$$\frac{dw_{rot}}{dt} = \frac{1}{2H_{rot}} \left[-\frac{P_{mech}}{w_{rot} + w_0} + D_{tg}(w_{gen} - w_{rot}) + k_{tg}\Delta\theta_m \right] \quad (24)$$

$$\frac{d(\Delta\theta_m)}{dt} = w_{base}(w_g - w_t) \quad (25)$$

w_{gen} denotes speed of generator, P_{elec} electric power, w_0 initial velocity, w_{rot} turbine speed, and P_{mech} mechanized power; stable state appears when $w_{gen} = w_{rot}$, so $d(\Delta\theta)/dt = 0$, & $P_{elec} = P_{mech}$. D_{tg} , K_{tg} , & w_{base} are constants. Mass's geometrical dissipation demonstrates inertial constant, inertial moment evaluated utilizing:

$$H_{rotor} = \frac{J_{rotor} w_{rotor}^2}{2P_n}; H_{gen} = \frac{J_{gen} w_{gen}^2}{2P_n} \quad (26)$$

Wind rotor's period of inactivity can be eliminated by:

$$J_{rotor} = \frac{1}{8} m_r R^2 \quad (27)$$

Mass and radius of rotor are denoted by symbols m_r and R , respectively. Stator terminal Generator output voltages in d-q frame expressed as:

$$V_d = R_d I + L_d \frac{dI_d}{dt} - \omega_{gen} L_q I_q \quad (28)$$

$$V_q = R_q I_q + L_q \frac{dI_q}{dt} + \omega_{gen} (L_d I_d + \varphi_f) \quad (29)$$

L shows inductance of generator's, R resistance, I Current along d-q coordinates, φ_f permanent magnetic flux, and ω_{gen} , PMSG's spinning speed.

$$\omega_{gen} = P_p \omega_{ref} \quad (30)$$

P_p represents pole pairs. Electromechanical rotational torque T_{gen} , given as:

$$T_{gen} = \frac{3}{2} P_p \omega_{ref} ((L_q - L_d) i_d i_q + \varphi_f i_q) \quad (31)$$

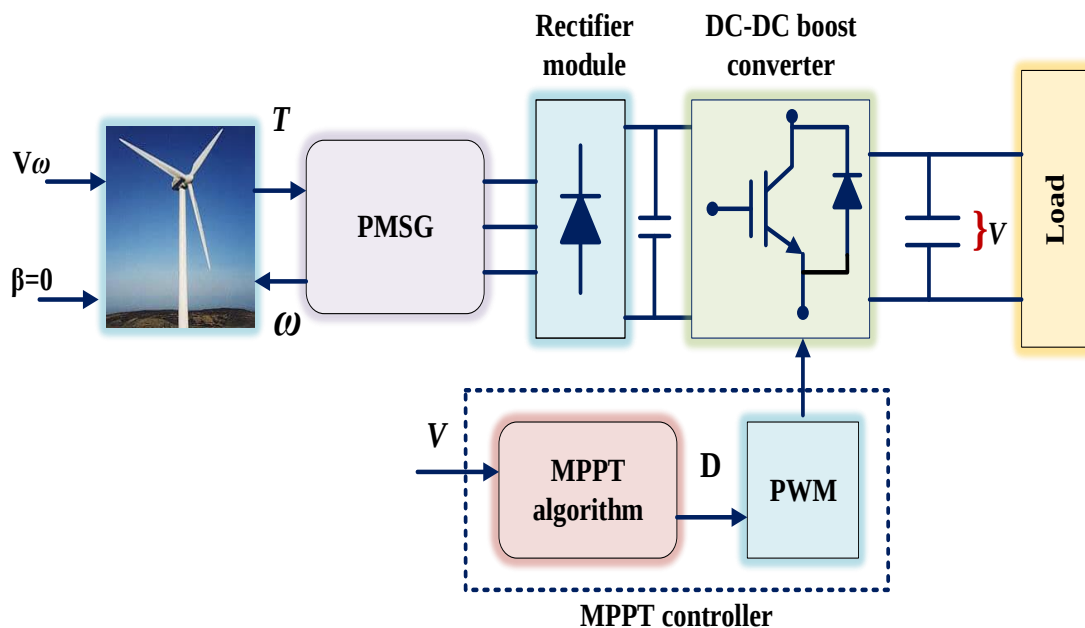


Figure 5. Illustration of PMSG wind network.

PV framework

Similar to WTGs, PV systems are variable power sources that primarily rely on the amount of solar light and surface temperature [47]. These factors are used to calculate the PV system power using Equation (32), which looks like this:

$$P_{PV} = \phi S \xi (1 - 0.005(T_A - 25)) \quad (32)$$

Where, ϕ fall within (9%-12%), S is efficiency of PV array; S is efficiency of PV panels cover (m^2); ξ is solar irradiance (kW/m^2); T_A often standardized at $25^\circ C$, is ambient temperature.

The PV system in the identical scenario with WTGs is defined by a first-order lag transfer function, which is described in Equation (33) as follows:

$$G_{PV}(s) = \frac{\Delta P_{PVG}}{\Phi_{PV}} = \frac{K_{PV}}{1 + sT_{PV}} \quad (33)$$

This study describes a fuzzy logic-based MPPT PV approach using MATLAB/Simulink. Block diagram of control method, which integrates fuzzy MPPT technique is shown in Figure 6. In Figure 8; I_{PV} , V_{PV} , p , S , and D show PV current, voltage, power, switch, and diode.

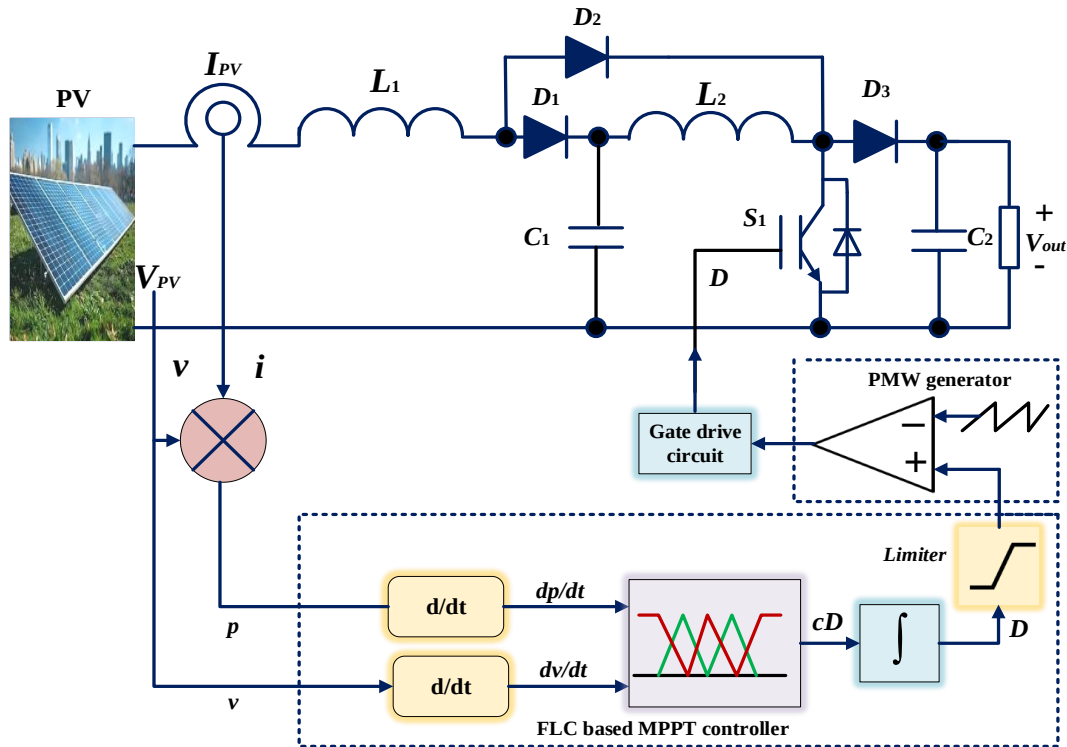


Figure 6. Schematic illustration of fuzzy MPPT solar system.

BESS framework with droop regulation

In addition to the robust growth of RESs, BESS has been assessed as a backup function to balance load demand and power supply in LFC over the last ten years. BESS devices are able to achieve precise frequency management by utilizing droop control to modify the state of charge (SOC) from LFC output [42].

SOC estimation of BESS

Frequently, system current is used to calculate the battery's state of charge. If the battery's interval voltage is contracted, the system is proportionate to the current. Lastly, by applying the energy idea by the transfer function and integrating power as Equations (34) and (35), we can directly ascertain the SOC of BESS:

$$SOC(t) = SOC_0 + \frac{1}{Eh} \int_{t_0}^t P_{BESS}(t) dt \quad (34)$$

$$\frac{\Delta SOC(s)}{\Delta P_{BESS}} = \frac{1}{Eh} \times \frac{1}{s} = \frac{1}{K_E s} \quad (35)$$

where SOC_0 is the initial value of SOC; E is a battery capacity (MWh); h is a factor of hour second ($h=3600$); P_{BESS} is a battery power (MW); $\Delta SOC = SOC - SOC_0$ and K_E is BESS energy in joule (BESS capacity in accordance the number of seconds). As shown in the following equation, the droop rate is determined when frequency fluctuations result in electricity being supplied to the grid:

$$\Delta P_{BESS}(t) = \frac{1}{R_{BESS}} \Delta f(t) \quad (36)$$

The relationship between SOC and frequency is displayed here, based on the relationship between SOC and power in Equation (35) and droop in Equation (36):

$$\frac{\Delta SOC(s)}{\Delta f(s)} = \frac{1}{R_{BESS}} \times \frac{1}{Eh} \times \frac{1}{s} = \frac{1}{R_{BESS} K_E s} \quad (37)$$

Droop control with SOC feedback-based offset

The droop control with SOC feedback is introduced in [42] with the main purpose of managing power flow, which complements LFC.

Based on Equation (37), to determine the BESS power in Equation (38), we subtract the frequency offset from the initial frequency variation.

$$\Delta P_{BESS}(t) = \frac{1}{R_{BESS}} [\Delta f(t) - f_{ofs}(t)] \quad (38)$$

$$f_{ofs}(t) = \Delta SOC(t) K_f \quad (39)$$

$$K_f = \frac{f_{ofs,max} - f_{ofs,min}}{SOC_{tot}} \quad (40)$$

In a large-scale system, installing multiple BESSs simultaneously is crucial, it brings sustainability and stability to the EPS based on reducing dramatic peak frequency fluctuations in the shortest possible time.

For BESS aggregation, installing BESS parallel with droop control can be represented as R_{BESS}/Y , where Y indicates the number of parallels. The capacity of the BESS can be expressed as XK_E , where X signifies multiple BESS units. Figure 7 depicts the detailed block diagram of BESS with droop control applied for LFC in EPS.

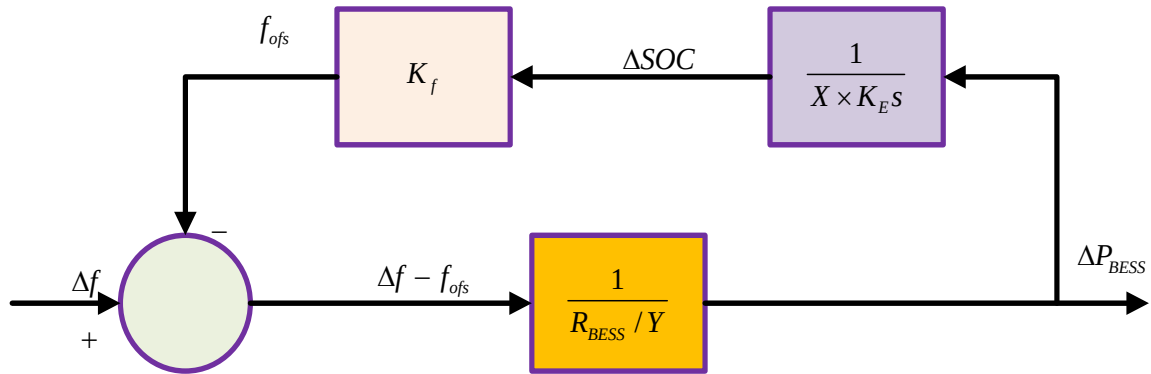


Figure 7: SOC feedback-based droop control with offset [42].

The tie-line, which promotes power exchange, controls the relationship between the two sectors. The power flow in the tie-line is represented by

$$\Delta P_{tie}(t) = \frac{2\pi T_{12}}{s} (\Delta f_1(t) - \Delta f_2(t)) \quad (41)$$

The frequency deviations in the respective areas are represented by $\Delta f_1(t)$ and $\Delta f_2(t)$, while T_{12} denotes the synchronizing coefficient. The configuration of the two-

area system is depicted in Figure 8. A detailed model is presented for analyzing and optimizing the dynamics and control strategies of the proposed power system, with the parameters outlined in Tables 1 and 2.

Table 1. Constraints values of thermal power network.

Restraint	Restraint value
Turbine constant time	0.5 s
Governor time constant	0.2 s
Generator moment of inertia	5 s
Governor's speed control	0.05 Pu
Turbine power capacity	250 MW
Frequency	60 Hz
Duty cycle	0.8

Table 2. Constraint values and electrical configurations of wind, solar, and BESS systems.

Features of PV	
Parallel strings	90
Module connected in series	55
Maximal output power	213.15 W
Voltage in an open circuit	36.3 V
Voltage at peak power	29 V
Temperature coefficient of open-circuit voltage	-0.36099
Every module's cell	60
Short circuit current	7.84 A
Current at peak power	7.35 A
Thermal coefficient	0.102
Specified temperature	25 °C, 1000 (W/m ²)
Ideal diode factor	0.98117
Resistance in parallel	313.3991 ohm
Series resistance	0.39383 ohm
Characteristics of PMSG wind turbine	
Mechanical output power	1400 kW
Base power of generator	1400 kW/0.94
Peak power (Pu)	0.95
Rotational speed of generator (Pu)	1.1
Stator phase resistance	0.0578 ohms
Wind speed	12 m/s
BESS	
K_f	0.1/60
K_E	1.8
R_{BESS}	0.2

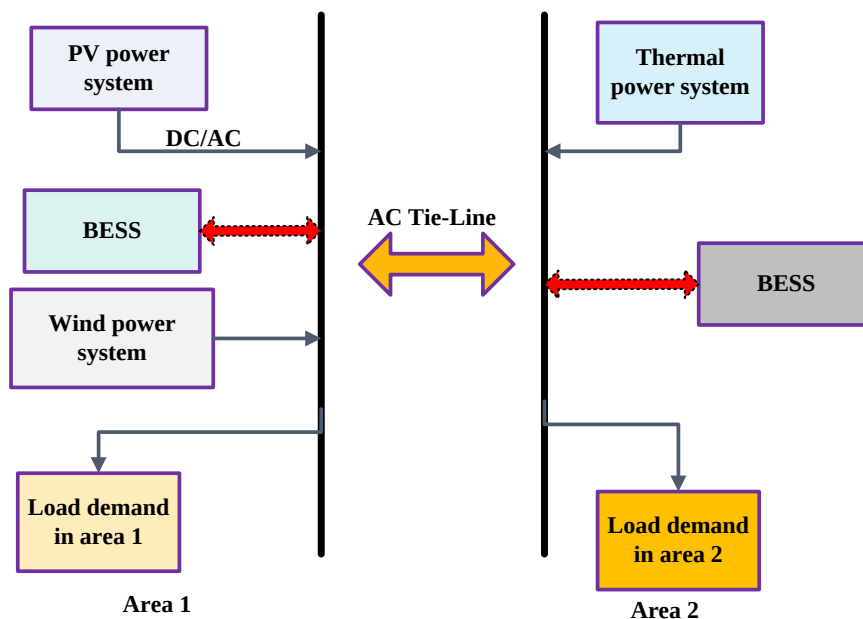
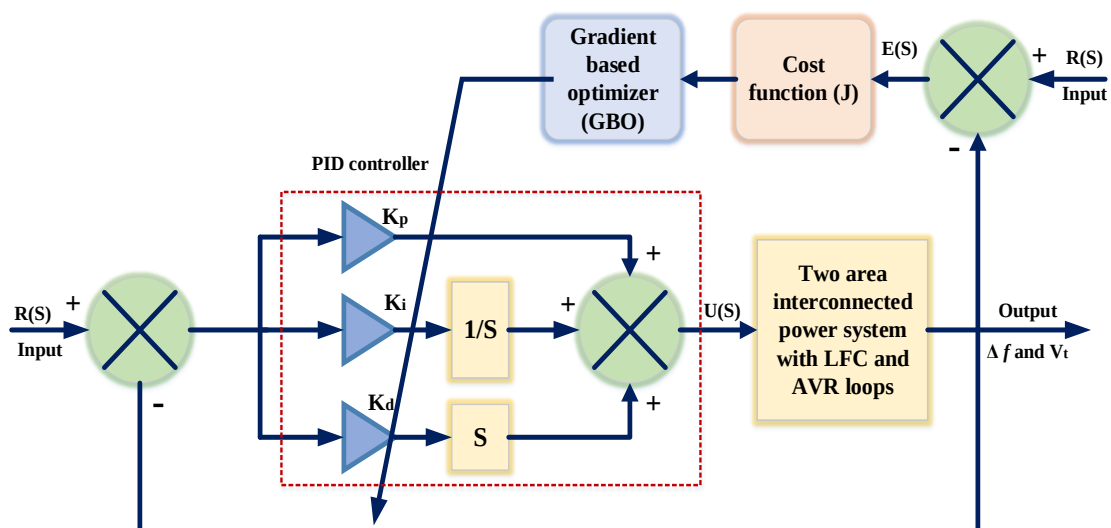


Figure 8. An illustration of the proposed power network.

Proposed Control Methodology

Figure 9a shows the suggested approach using IPS. The four-area IPS was coupled LFC and AVR controlled by a PID controller. Additionally, a number of additional controllers, including I-PD, TID, and I-P, have been investigated in order to compare their outcomes with those of GBO-PID. In this part, the suggested PID and the other controllers are described.



a)

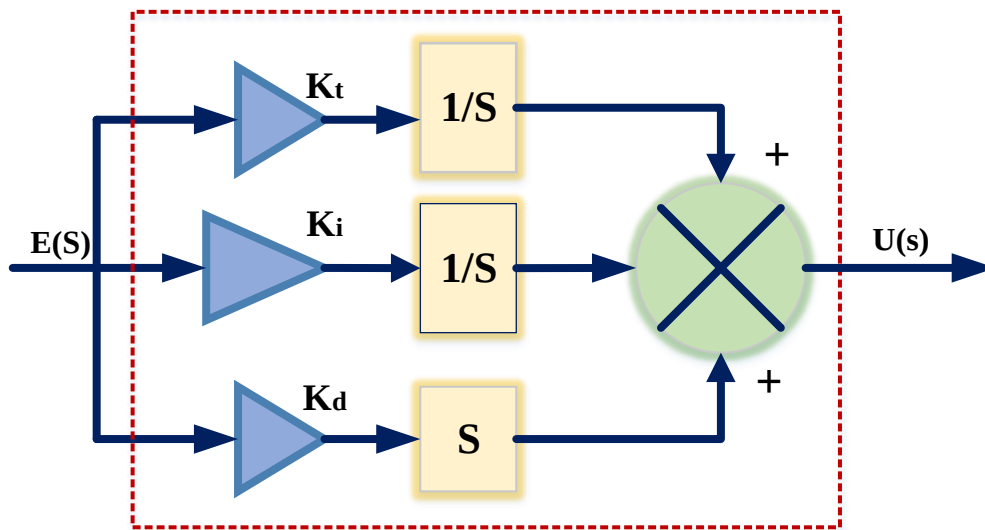
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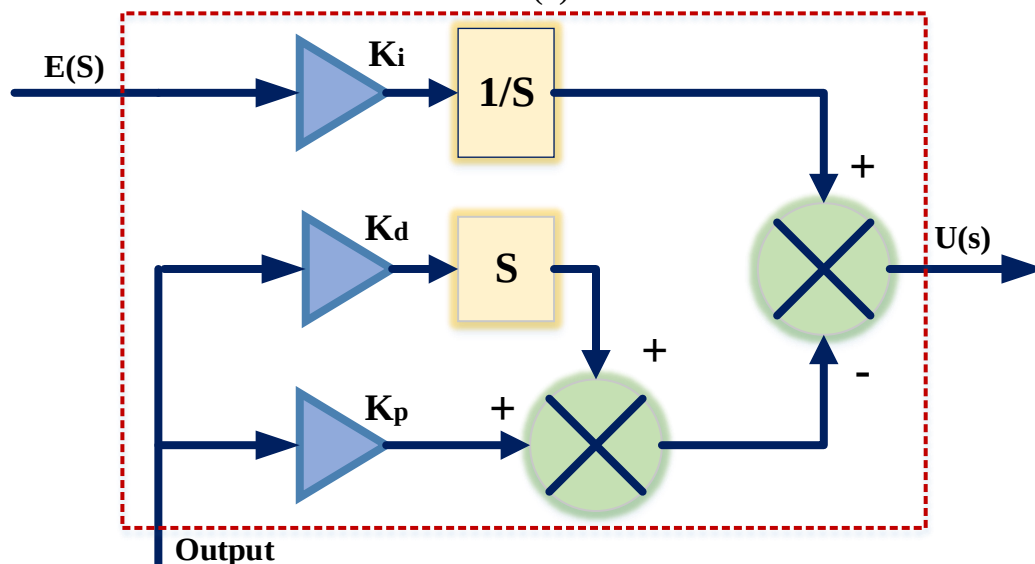
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(b)



(c)

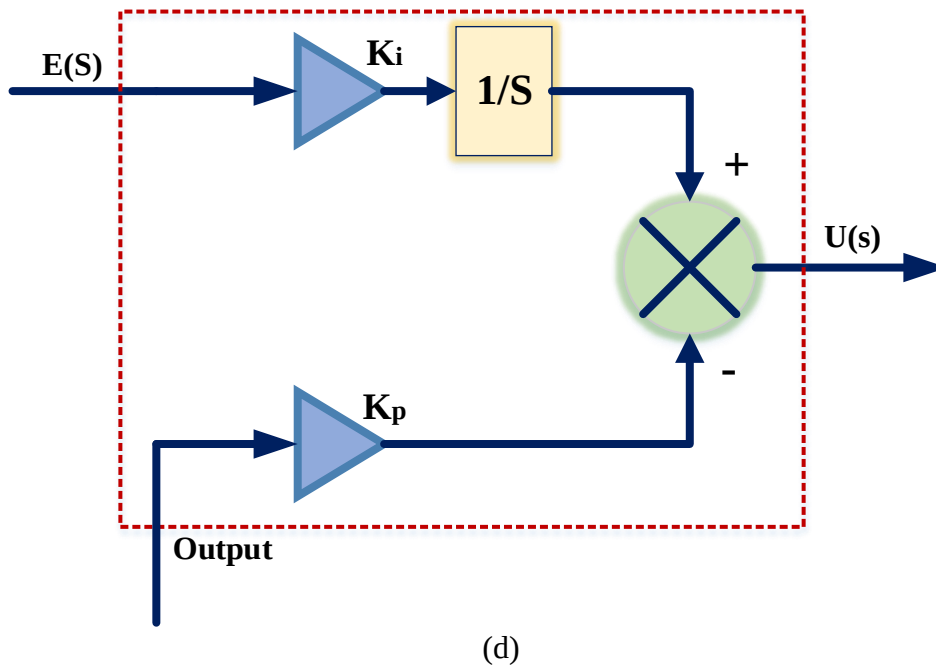


Figure 9. (a) The suggested method of control. TID controller (b). I-PD controller (c). I-P controller (d).

Due to its inherited qualities of straightforward design and superior operating efficiency, the classic PID controller is widely used in the industrial sector. A feedback-based control loop system, the proportional integral derivative (PID) controller continuously computes an error signal as the difference between a measured process variable and the set point in order to produce the control signal for the plant. K_p , K_i , and K_d are the three gain coefficients of the PID controller. The PID controller's ($U_{PID}(s)$) control signal can be expressed as follows:

$$U_{PID}(s) = \left(K_p + \frac{K_i}{s} + K_d s \right) E(s) \quad (42)$$

$$E(s) = \gamma(s) - R(s) \quad (43)$$

where error, output, and reference signals are indicated by the symbols $E(s)$, $Y(s)$, and $R(s)$ respectively. The proportional term of PID is modified, but the design of the TID controller is the same as that of PID. The modification is the substitution of $K_t(s)^{-1/n}$ for the proportional gain term in PID, where n is a real number and K_t is the gain. Fractional and integer order controllers are combined in TID. Because of its outstanding dynamic properties, disruptions are swiftly eliminated. The block diagram for the TID controller is displayed in Figure 9b. K_t , K_i , and K_d are the three gain coefficients of the TID controller. The TID controller's control signal ($U_{TID}(s)$) can be expressed as follows:

$$U_{TD}(s) = \left(K_t s^{\frac{1}{n}} + \frac{K_i}{s} + K_d s \right) E(s) \quad (44)$$

The transient responsiveness of the controller, specifically the overshoot time, can be enhanced by the I-PD controller. The integrator controller is positioned in the feed-forward direction, whereas the proportional and derivative terms are positioned in the I-PD controller's feedback path. The I-PD controller's block diagram is displayed in Figure 9c. The three gain coefficients of the I-PD controller are K_i , K_p , and K_d . The I-PD controller's ($U_{I-PD}(s)$) control signal can be expressed as follows:

$$U_{I-PD}(s) = \frac{K_i}{s} E(s) - (K_p + K_d s) \gamma(s) \quad (45)$$

In an I-P controller, the integrator controller is positioned in the feed-forward direction, while only the proportional term is in the feedback path. Figure 9d displays the I-P controller's block diagram. Both K_i and K_p are gain coefficients in the I-P controller. One way to express the control signal produced by the I-P controller ($U_{I-P}(s)$) is as follows:

$$U_{I-P}(s) = \frac{K_i}{s} E(s) - K_p \gamma(s) \quad (46)$$

The optimal gains of controllers, as emphasized in Equations (42) and (44)–(46), are calculated using the GBO that is presented in the next section. Further, ITSE [1] has been employed as an error specification index for the GBO-PID control methodology's optimal control of the LFC and AVR loops in the four-area IPS. Equation (47) yields the cost function (J) for the IPS.

$$J_{ITSE} = \int_0^T t \left[\Delta f^2 + \Delta V_t^2 + \Delta P_{tie}^2 \right] dt \quad (47)$$

Where

$$\Delta f^2 = \Delta f_1^2 + \Delta f_2^2$$

$$\Delta V_t^2 = \Delta V_{t1}^2 + \Delta V_{t2}^2 \quad (48)$$

$$\Delta P_{tie}^2 = \Delta P_{tie1}^2 + \Delta P_{tie2}^2$$

$$\Delta V_{t1} = V_{ref} - V_{t1}$$

$$V_{t2} = V_{ref} - V_{t2} \quad (49)$$

$$\Delta P_{ptie1} = \Delta P_{ptie12}$$

GBO is used to minimize the cost function provided by Equation (47) in order to obtain the controller's ideal gains.

Gradient-Based Optimizer (GBO)

The design of a controller that can maintain terminal voltage and load frequency within specified limits is a particularly difficult issue for control system experts due to the complexity of the dual-area IPS power system with four generation units. In the control of IPSs, there has been a lot of interest in nature-inspired computation algorithms that can solve challenging technical difficulties. In this study, a PID controller tuned with a GBO was used to successfully regulate the load frequency and the terminal voltage of a dual-area tie-line IPS. The GBO algorithm's use in automatic voltage control applications inspired the authors to investigate its potential for controlling both terminal voltage and load frequency simultaneously[32]. In terms of settling time, overshoot percentage, and undershoot percentage, GBO-based control techniques yielded acceptable time responses. GBO was created in 2020[41]. The gradient-based approach of Newton served as the model for the GBO algorithm, which employs a variety of vectors to find the problem's solution space. Mutational techniques like gradient search rules and local escaping are used to conduct this search. For this algorithm to find the optimal solution, an equilibrium point where the slope is zero must be found. Using this method, determining the search directions necessitates calculating the derivatives of the objective function in addition to restrictions. The initial population is created at random, and the search direction is established using the data from earlier iterations. Until a specific requirement is met, these cycles are repeated. The following are the steps in a GBO[48].

GBO INITIALIZATION

The following is how the GBO population is initialized:

$$X_n = X_{\min} + rand(0,1) \times (X_{\max} - X_{\min}) \quad (50)$$

$$X_{n,d} = [X_{n,1}, X_{n,2}, \dots, X_{n,D}] \quad (51)$$

where the population trajectories are represented by $n = [1, 2, \dots, N]$ and the search space dimensions are indicated by $d = [1, 2, \dots, D]$; The decision variable's bounds are denoted by $X_{\min}$ and $X_{\max}$, while $rand(0,1)$ produces a uniform random integer between 0 and 1.

GRADIENT SEARCH RULE (GSR)

Finding the extreme point at which the gradient equals zero is how the gradient-based method, which is the foundation of GSR, determines the best answer. Accelerating the rate of convergence and enhancing the exploring inclination are the goals of using GSR. A new position can be expressed using the Taylor series and the numerical gradient technique (x_{n+1}):

$$x_{n+1} = x_n - \frac{2\Delta x \times f(x_n)}{f(x_n + \Delta x) - f(x_n - \Delta x)} \quad (52)$$

The surrounding places of x_n are represented by $x_n + \Delta x$ and $x_n - \Delta x$ in the GBO algorithm. Position $x_n + \Delta x$ is less fit (x_{worst}) than x_n , and position $x_n - \Delta x$ is more fit (x_{best}) than x_n . The GSR can be expressed as follows:

$$GSR = randn \times \frac{2\Delta x \times x_n}{(x_{worst} - x_{best} + \varepsilon)} \quad (53)$$

where $randn$ is a random integer drawn from a normal distribution, ε is a tiny value between 0 and 0.1, and Δx is the change in position following each iteration. To attain equilibrium between the periods of exploration and exploitation, the modified formulation of GSR can be expressed as follows:

$$GSR = randn \times \rho_1 \times \frac{2\Delta x \times x_n}{(x_{worst} - x_{best} + \varepsilon)} \quad (54)$$

where ρ_1 is a random number computed as:

$$\rho_1 = (2 \times rand \times \alpha) - \alpha \quad (55)$$

$$\alpha = \left| \beta \times \sin\left(\frac{3\pi}{2} + \sin\left(\beta \times \frac{3\pi}{2}\right)\right) \right| \quad (56)$$

$$\beta = \beta_{\min} + (\beta_{\max} - \beta_{\min}) \times \left(1 - \left(\frac{m}{M}\right)^3\right)^2 \quad (57)$$

where m indicates the current iteration, M is the total number of iterations, and $\beta_{\max}$ and $\beta_{\min}$ are 1.2 and 0.2, respectively. α is a representation of the sine function that shows the transition from exploration to exploitation. One way to express the difference Δx between a position selected at random (x_{r1}^{m1}) and the best candidate solution (x_{best}) is as follows:

$$\Delta x = rand(1:N) \times |step| \quad (58)$$

$$step = \frac{(x_{best} - x_{r1}^m) + \delta}{2} \quad (59)$$

$$\delta = 2 \times rand \times \left(\left| \frac{x_{r1}^m + x_{r2}^m + x_{r3}^m + x_{r4}^m}{4} - x_n^m \right| \right) \quad (60)$$

where the random numbers r_1, r_2, r_3 , and r_4 have varying values and range from 1 to N . One way to express the updated position (x_{n+1}) is as follows:

$$x_{n+1} = x_n - GSR \quad (61)$$

The direction of movement (DM), which can be expressed as follows, is introduced for improved use of the area near x_n .

$$DM = rand \times \rho_2 \times (x_{best} - x_n) \quad (62)$$

where the random number ρ_2 is calculated as follows:

$$\rho_2 = (2 \times rand \times \alpha) - \alpha \quad (63)$$

GSR and DM can be used to determine the changed position x_1^m as follows:

$$X1_n^m = x_n^m - GSR + DM \quad (64)$$

$$X1_n^m = x_n^m - randn \times \rho_1 \times \frac{2\Delta x \times x_n^m}{(x_{worst} - x_{best} + \Sigma)} \quad (65)$$

The best vector's x_{best} location can be changed to produce the new x_2^m one by using x_n^m :

$$X2_n^m = x_{best} - randn \times \rho_1 \times \frac{2\Delta x \times x_n^m}{(yp_n^m - pq_n^m + \Sigma)} + rand \times \rho_2 \times (x_{r1}^m - x_{r2}^m) \quad (66)$$

where

$$yp_n = rand \times \left(\frac{[z_{n+1} + x_n]}{2} - rand \times \Delta x \right) \quad (67)$$

$$cq_n = rand \times \left(\frac{[z_{n+1} + x_n]}{2} - rand \times \Delta x \right) \quad (68)$$

and z_{n+1} represents a vector.

The new solution (x_n^{m+1}) can be defined at the next iteration as:

$$x_n^{m+1} = r_a \times (r_b \times x_{1n}^m + (1 - r_b) \times X_{2n}^m) + (1 - r_a) \times X_{3n}^m \quad (69)$$

Where

$$X_{3n}^m = 35X_N^m - \rho_1 \times (X_{2n}^m - X_{1n}^m) \quad (70)$$

and r_a and r_b are random numbers between 0 and 1.

LOCAL ESCAPING OPERATOR (LEO)

A LEO is added to the GBO algorithm to increase its capacity to tackle difficult issues. The following pseudo code can be used to reach the LEO solution X_{LEO} :

$$\begin{aligned} & \text{if } rand \leq pr \\ & \text{if } rand \leq 0.5 \\ X_{LEO}^m &= X_n^{m+1} + f_1 \times (u_1 \times x_{best} - u_2 \times x_K^m) + f_2 \times \rho_1 \times (u_3 \times (X_{2n}^m - X_{1n}^m) + u_2 \times (x_{r1}^m - x_{r2}^m)) / 2 \end{aligned} \quad (71)$$

$$X_n^{m+1} = X_{LEO}^m$$

else

$$X_{LEO}^m = X_n^{m+1} + f_1 \times (u_1 \times x_{best} - u_2 \times x_K^m) + f_2 \times \rho_1 \times (u_3 \times (X_{2n}^m - X_{1n}^m) + u_2 \times (x_{r1}^m - x_{r2}^m)) / 2 \quad (72)$$

$$X_n^{m+1} = X_{LEO}^m$$

end

end

where the best answer is indicated by x_{best} ; X_{r1}^m , X_{r2}^m and X_K^m the other solutions are created at random; f_2 is a random number with a mean of 0 and a standard deviation of 1, while f_1 is a random number between -1 and 1; The probability is denoted by pr . Thus, it is possible to obtain u_1 , u_2 , and u_3 as follows:

$$u_1 = L_1 \times 2 \times rand + (1 - L_1) \quad (73)$$

$$u_2 = L_1 \times 2 \times rand + (1 - L_1) \quad (74)$$

$$u_3 = L_1 \times 2 \times rand + (1 - L_1) \quad (75)$$

where L_1 is expressed as follows: L_1 has a value of 1 if parameter u_1 is less than 0.5, and 0 otherwise X_k^m can be written as:

$$x_K^m = \begin{cases} x_{rand} & \text{if } u_2 < 0.5 \\ x_p^m & \text{otherwise} \end{cases} \quad (76)$$

where x_{rand} represents the new solution and x_p^m denotes random solution of the population ($P \in [1, 2, \dots, N]$).

$$x_{rand} = X_{\min} + rand(0,1) \times (X_{\max} - X_{\min}) \quad (77)$$

$$x_K^m = L_2 \times x_p^m + (1 - L_2) \times x_{rand} \quad (78)$$

Whereas L_2 has a value of 0 normally, it has a value of 1 if parameter u_2 is less than 0.5. Randomly selecting values for the parameters u_1 , u_2 , and u_3 increases population diversity and helps to steer clear of local optimal solutions. Figure 10 shows the GBO flow chart.

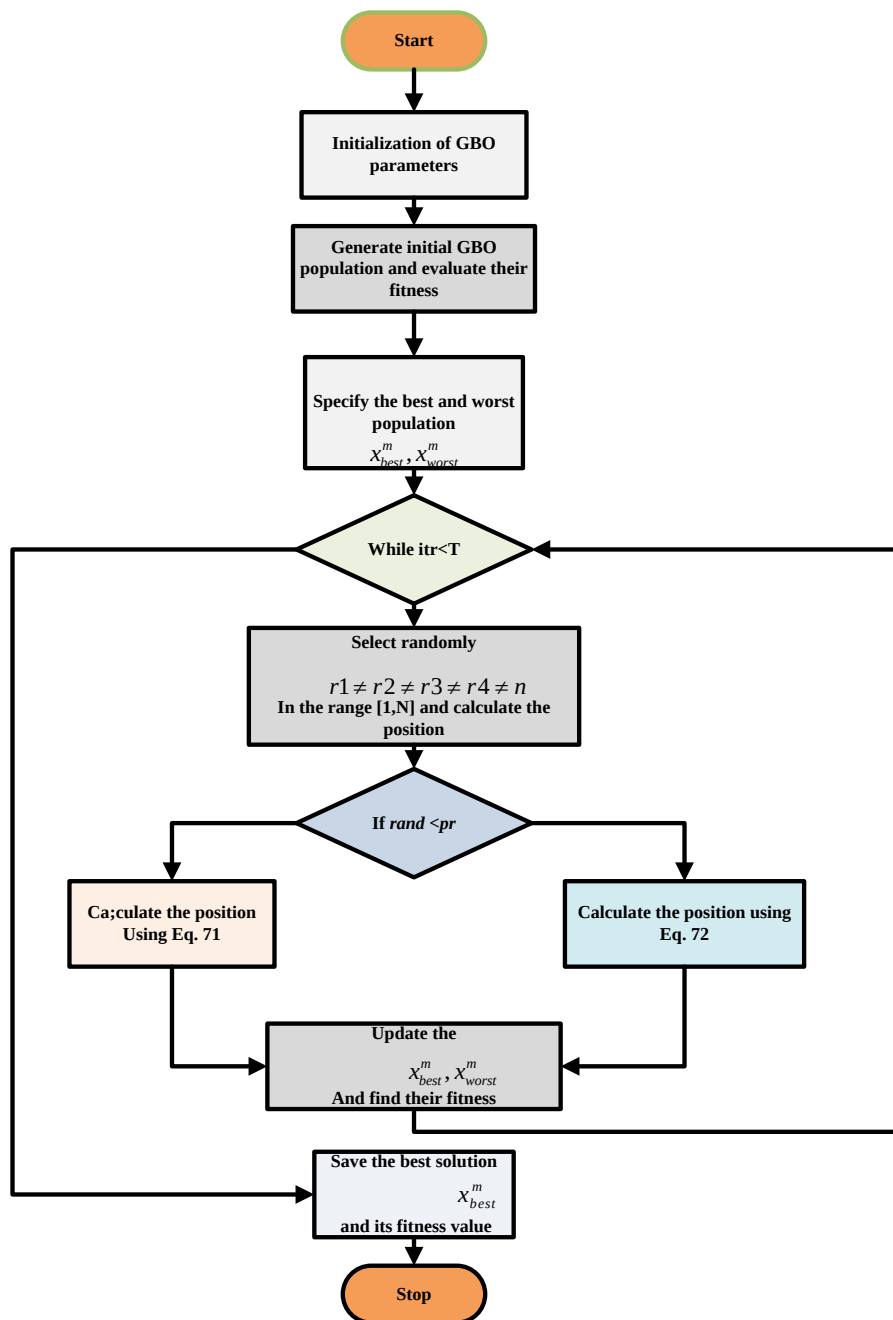


Figure 10. GBO flowchart.

Simulations and Discussion of Results

The proposed control mechanism was validated through extensive simulations in MATLAB/Simulink. First, GBO-based control approaches were used to thoroughly analyze a dual-area, four-source tie-line IPS with 5% SLP (0.05 p.u.) in each area. After that, a thorough sensitivity study was conducted by altering the system settings in every section. There are 90 solutions in the population, but the simulation took into account 140

iterations to find the best one. The reference terminal voltage was determined by taking the step input per unit. Remember that each simulation's settling time was calculated with a margin of $\pm 2\%$.

FOUR-AREA tie-line IPS WITH COMBINED AVR-LFC

The dual-area tie-line IPS model under investigation is shown in Figure 11. Tables 2 and 3 provide the proposed network's system parameters. The GBO-PID, GBO-I-PD, GBO-TID, and GBO-I-P control methodologies' ideal parameters are listed in Table 4. A thorough comparison of the suggested GBO-PID, GBO-I-PD, GBO-TID, and GBO-I-P control methodologies is provided in this section. While Table 5 shows the numerical findings of LFC performance parameters for the suggested system using the GBO-PID, GBO-I-PD, GBO-TID, and GBO-I-P control techniques, Figure 12 shows the frequency deviation response curves. In terms of settling time, it is evident that the suggested GBO-PID control technique produced very excellent LFC responses. At the expense of percent (%) overshoot and undershoot, GBO-PID produced settling durations of 0.3, 0.2, and s in area-1 and area-2 LFC, respectively, which are superior than GBO-I-PD, GBO-TID, and GBO-I-P control techniques. In comparison to other control approaches, GBO-I-PD produced a better undershoot response (-0.032) with zero percent overshoot. GBO-I-PD produced better percentage overshoot (0.006%) and undershoot (-0.098) responses in area-2 LFC when compared to other control approaches. The steady-state errors in areas 1 and 2 are 0.0007 and 0.0006, respectively.

Table 4. Ideal controller parameter.

Area	GBO I-P		GBO TID		GBO I PD		GBO PID	
	Controller Parameter	Value	Controller Parameter	Value	Controller Parameter	Value	Controller Parameter	Value
Area 1	Kp1	0.63	Kt1	0.64	Ki1	0.0001	Kp1	1.26
	Ki1	1.64	Ki1	1.22	Kp1	1.95	Ki1	1.19
	-	-	Kd1	0.27	Kd1	1.63	Kd1	1.62
	Kp2	1.36	Kt2	0.55	Ki2	1.78	Kp2	1.11
	Ki2	1.79	Ki2	0.83	Kp2	1.54	Ki2	1.03
	-	-	Kd2	1.22	Kd2	0.61	Kd2	0.27
Area 2	Kp3	1.22	Kt3	1.13	Ki3	0.23	Kp3	1.69
	Ki3	0.49	Ki3	1.08	Kp3	0.37	Ki3	0.98
	-	-	Kd3	0.42	Kd3	0.48	Kd3	1.08
	Kp4	0.78	Kt4	0.67	Ki4	0.11	Kp4	1.31
	Ki4	0.55	Ki4	0.19	Kp4	0.63	Ki4	1.09
	-	-	Kd4	0.73	Kd4	0.68	Kd4	0.75
	ITSE	1.94	ITSE	1.98	ITSE	2.57	ITSE	0.49

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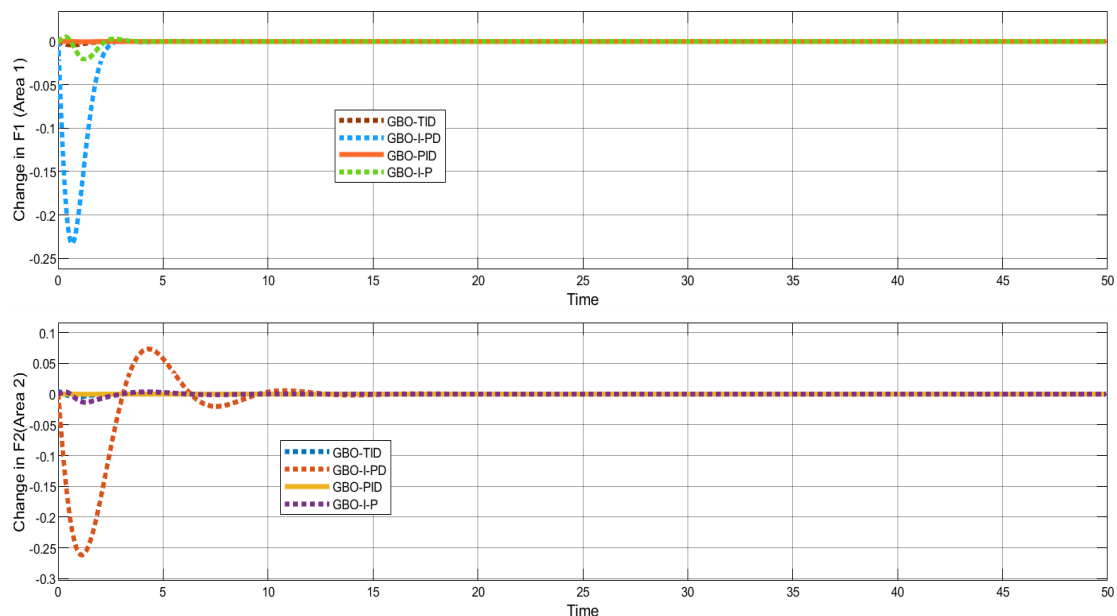


Figure 11. LFC responses in area 1 and 2.

Table 5. LFC loop numerical results.

Control Strategy	Area-1				Area-2			
	Settling Time	% Overshoot	% Undershoot	% s-s error	Settling Time	% Overshoot	% Undershoot	% s-s error
GBO-PID	0.3	0.14	-0.53	0.0007	0.2	0.23	-0.79	0.0006
GBO-I-PD	4.3	0.28	-0.032	0.03	11.3	0.006	-0.098	0.31
GBO-TID	2.9	0.33	-0.08	0.01	0.5	0.012	-0.45	0.01
GBO-I-P	4.1	0.0071	-0.04	0.02	4.5	0.036	-0.33	0.02

While Table 6 shows the numerical results of AVR performance specifications produced in areas 1 and 2 using the GBO-PID, GBO-I-PD, GBO-TID, and GBO-I-P control techniques, respectively, Figure 12 shows the terminal voltage response curves. In comparison to GBO-TID and GBO-I-P control techniques, which are superior to GBO-I-PD, GBO-TID, and GBO-I-P control methodologies, GBO-PID offered a settling time of 0.3 s for area-1 AVR and 0.2 s for area 2. In area-1 AVR, GBO-I-PD outperformed all other control techniques with a settling time of 6.9 s and an overshoot response of 0.48%. In area-2 AVR, GBO-PID produced an overshoot of 1.437%, outperforming GBO-I-PD, GBO-TID, and GBO-I-P control techniques. It is evident that the AVR responses generated by the proposed GBO-PID control technique are highly satisfying in terms of settling time and overshoot percentage.

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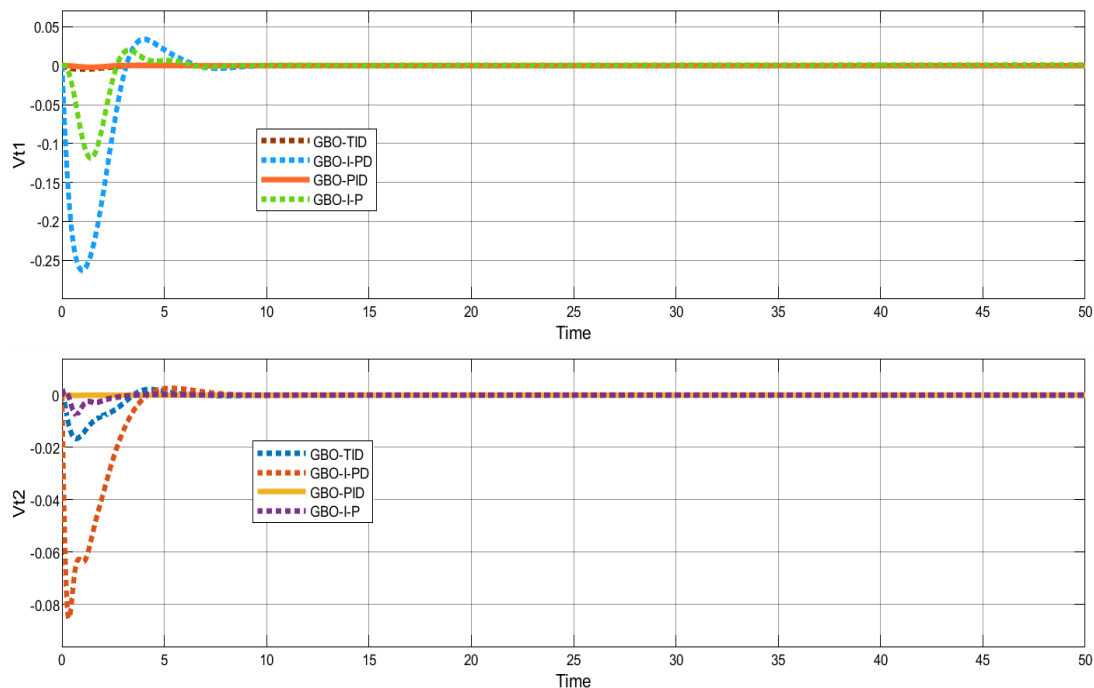


Figure 12. AVR responses in areas 1 and 2.

Table 6. AVR loop numerical results.

Control Strategy	Area-1				Area-2			
	Settling Time	% Overshoot	% Undershoot	% s-s error	Settling Time	% Overshoot	% Undershoot	% s-s error
GBO-PID	0.27	0.526	0.961	0.0005	0.18	1.437	1.635	0.0005
GBO-I-PD	6.9	1.638	2.681	0.03	5.2	-0.083	1.596	0.001
GBO-TID	2.9	0.714	1.658	0.002	4.8	2.591	3.185	0.0001
GBO-I-P	6.7	22.659	15.673	0.01	3.9	0.505	1.983	0.002

Figure 13 displays the tie-line power deviation responses, and Table 7 displays the numerical outcomes of the tie-line power performance parameters for areas 1, 2, 3, and 4. As can be shown, the tie-line power deviation responses generated by the proposed GBO-PID control technique were extremely satisfying in terms of settling time. GBO-PID outperformed GBO-I-PD, GBO-TID, and GBO-I-P control approaches, yielding settling durations of 0.3 and 0.2 s in area-1 and area-2, respectively. In comparison to previous control approaches, GBO-TID provided a better overshoot response (0.012%) and GBO-I-PD produced a better undershoot response (−0.0035) in terms of area-1 tie-line power deviation. In terms of area-2 tie-line power deviation, GBO-PID produced a 0.0025% overshoot and a 0.0093 undershoot, outperforming GBO-I-PD and GBO-I-P control techniques.

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Furthermore, in terms of area-2 tie-line power deviation, GBO-TID had a better undershoot response (0.0053) than alternative control approaches.

Table 7. Tie-line power deviations and their numerical results.

Control Strategy	Area-1				Area-2			
	Settling Time	% Overshoot	% Undershoot	% s-s error	Settling Time	% Overshoot	% Undershoot	% s-s error
GBO-PID	0.3	0.526	0.961	0.0005	0.2	0.0025	0.0093	0.0005
GBO-I-PD	3.6	1.638	-0.0035	0.03	3.9	-0.083	1.596	0.001
GBO-TID	1.1	0.012	1.658	0.002	3.8	2.591	0.0053	0.0001
GBO-I-P	5.3	22.659	15.673	0.01	6.9	0.505	1.983	0.002

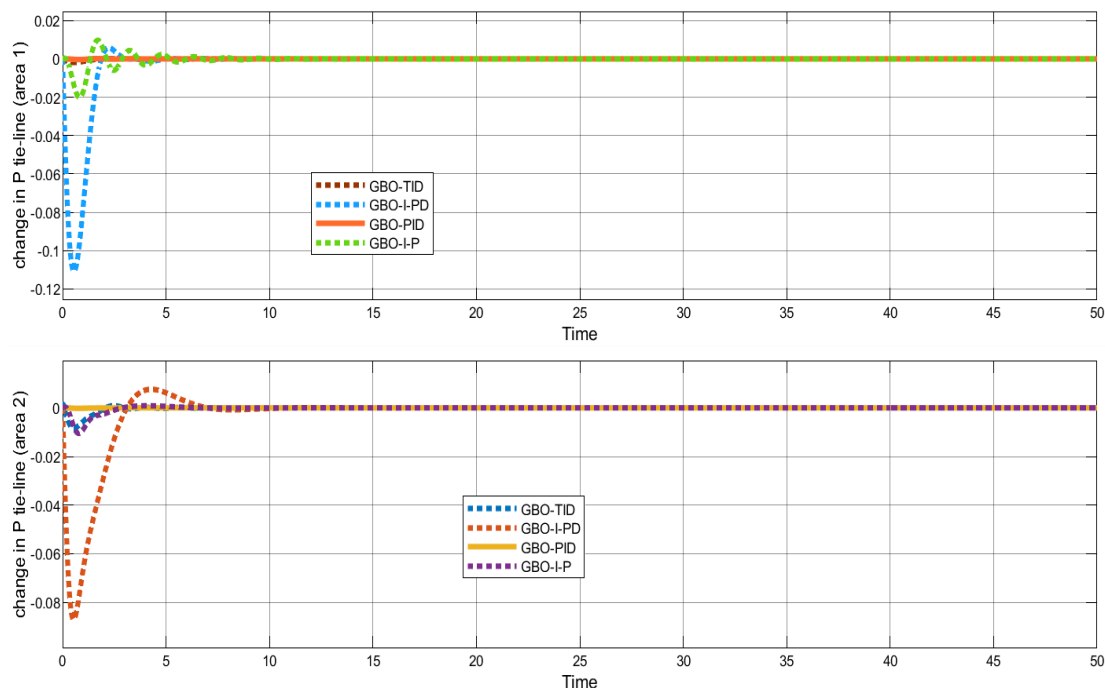


Figure 13. Responds to tie-line power deviations.

SENSITIVITY ANALYSIS

This section uses a multi-source, dual-area IPS with a combined LFC and AVR system to assess the robustness of the suggested GBO-PID control technique under dynamic system conditions. Robustness was tested by varying the turbine time constant (T_{tr}) and speed control factor (R) by $\pm 25\%$ from their nominal values. Under these parameter adjustments, the GBO-PID controller's LFC, AVR, and tie-line power responses are shown in Figures 14–19, and the corresponding numerical findings for LFC dynamic performance metrics are compiled in Tables 8–10. The findings

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indicate that the terminal voltage, frequency variation, and tie-line power variation responses essentially stay the same even with the $\pm 25\%$ variation in system parameters. Furthermore, there is little fluctuation in performance metrics including steady-state error, % overshoot, percentage undershoot, and settling time. These results demonstrate that the suggested GBO-PID control strategy is very reliable and does not need to be adjusted for Ttr and R parameter changes of up to $\pm 25\%$.

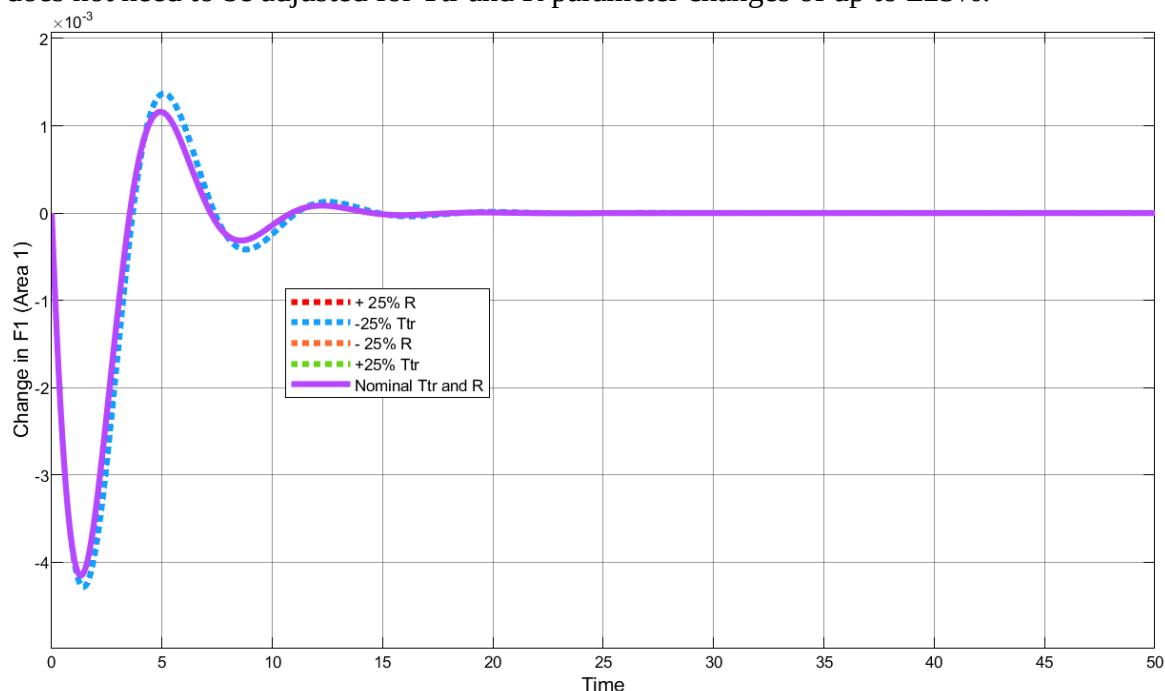


Figure 14. LFC responses in region 1 with variations of $\pm 25\%$ in system parameters.

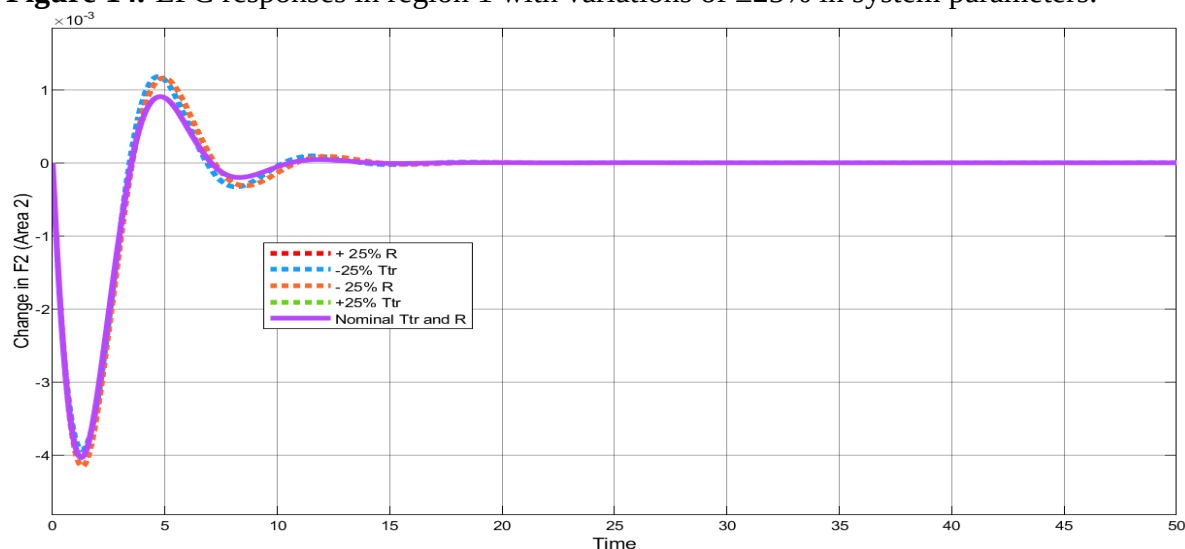


Figure 15. LFC responses in region 2 with variations of $\pm 25\%$ in system parameters.

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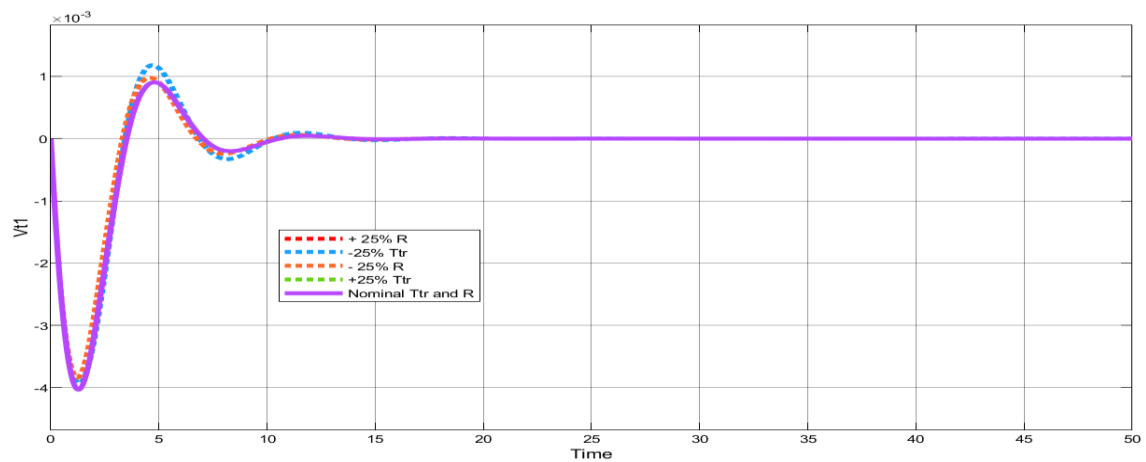


Figure 16. AVR responses in region 1 with $\pm 25\%$ system parameter alterations.

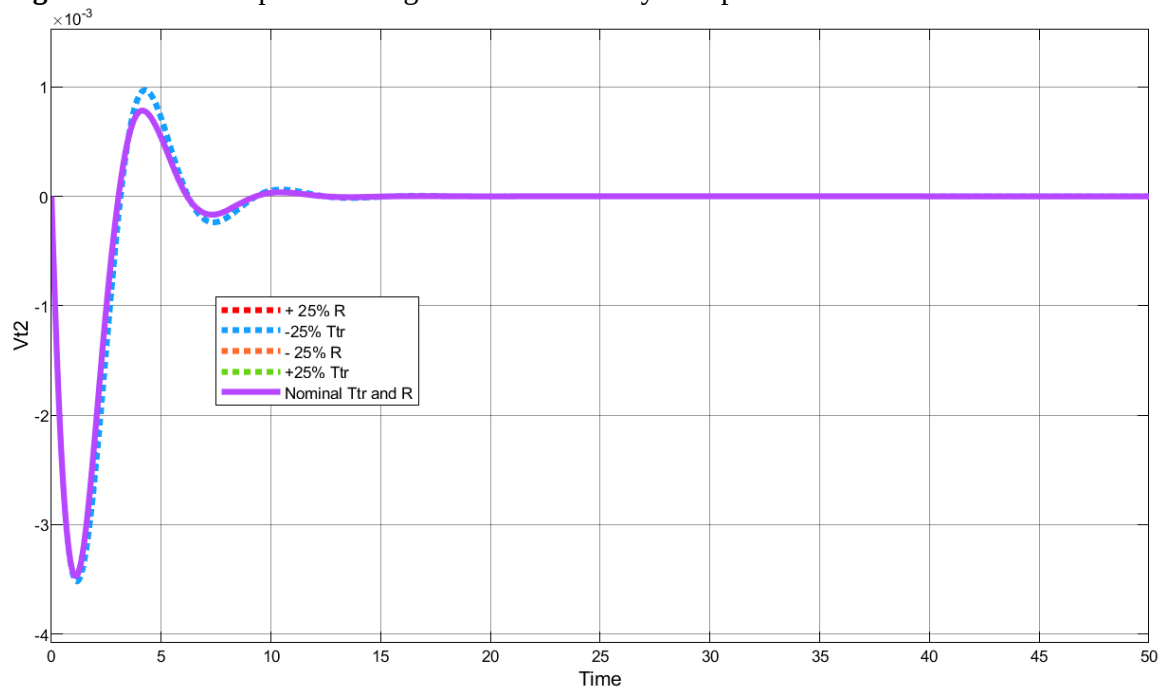


Figure 17. AVR responses in region 2 with system parameter variations of $\pm 25\%$.

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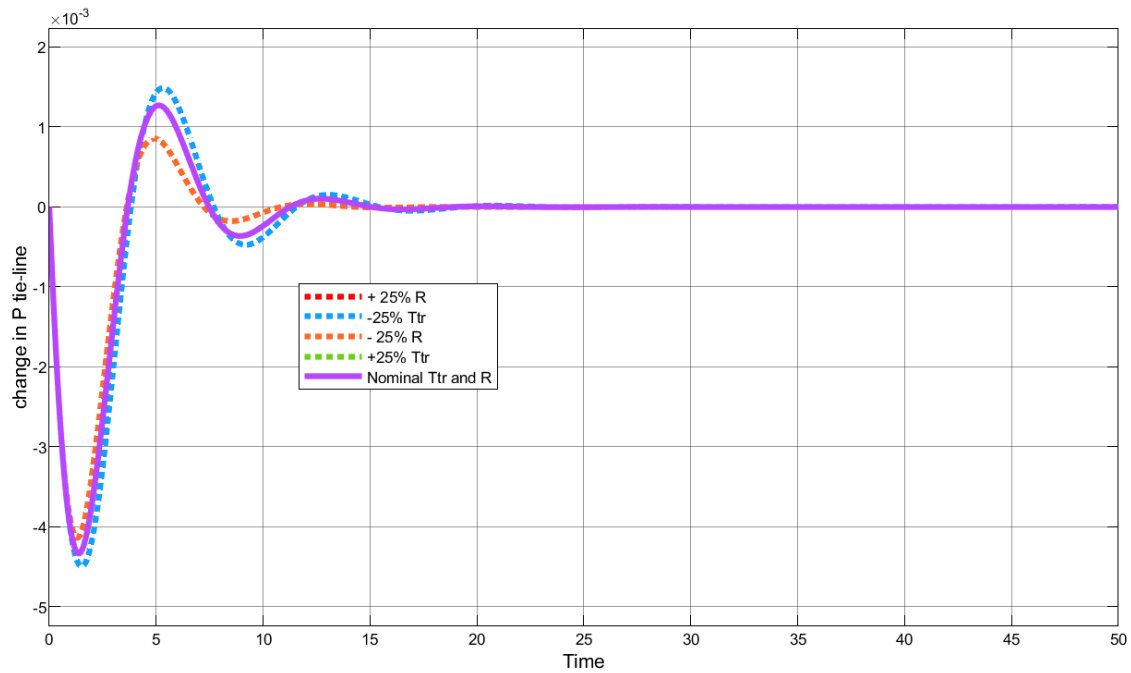


Figure 18. Tie-line power variation responses in region 1 with system parameter variations of $\pm 25\%$.

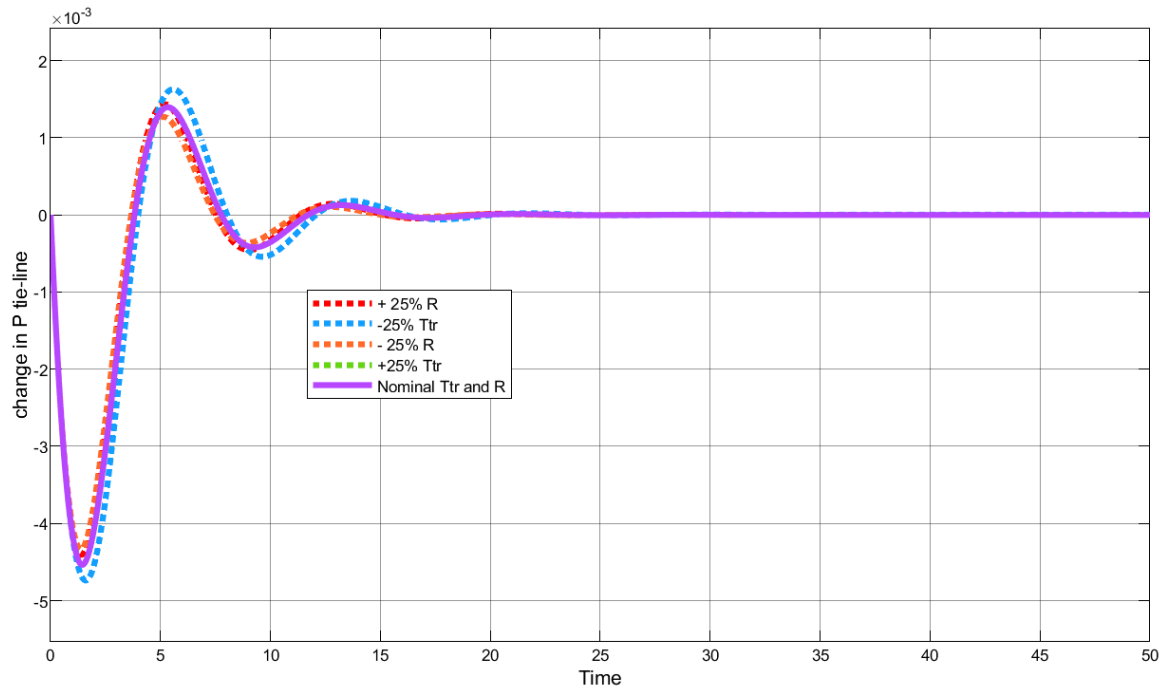


Figure 19. Responses to tie-line power deviations in region 2 with $\pm 25\%$ changes in system parameters.

Table 8 LFC numerical results employing the GBO-PID control methodology with a $\pm 25\%$ variation in system parameters.

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Case	Area-1				Area-1			
	Settling Time	% Overshoot	% Undershoot	% s-s Error	Settling Time	% Overshoot	% Undershoot	% s-s Error
–25% Ttr area 1 and area 2	15	1.526	14.135	0.08	12.9	0.526	0.961	0.06
–25% R area 1 and area 2	15.1	1.638	3.983	0.082	13.1	1.638	2.681	0.055
Nominal Values	14.8	0.714	3.151	0.077	11.7	0.714	1.658	0.05
–25% Ttr area 1 and area 2	15.4	1.659	4.738	0.084	12.6	22.659	15.673	0.059
–25% R area 1 and area 2	15.3	1.437	1.618	0.082	13.3	0.451	0.915	0.062

Table 9. AVR numerical results using the GBO-PID control approach with $\pm 25\%$ system parameter fluctuations.

Case	Area-1				Area-1			
	Settling Time	% Overshoot	% Undershoot	% s-s Error	Settling Time	% Overshoot	% Undershoot	% s-s Error
–25% Ttr area 1 and area 2	11.4	1.419	12.722	0.0736	10.2	0.494	0.893	0.0618
–25% R area 1 and area 2	11.7	1.523	3.585	0.07544	11.6	1.540	0.493	0.05665
Nominal Values	10.2	0.664	2.836	0.07084	9.6	0.671	1.543	0.0515
–25% Ttr area 1 and area 2	11.2	1.543	4.264	0.07728	10.9	0.299	1.577	0.06077
–25% R area 1 and area 2	11.8	1.336	1.456	0.07544	11.2	0.424	0.851	0.06386

Table 10. numerical outcomes of tie-line power variation responses utilizing the GBO-PID control technology with $\pm 25\%$ system parameter variations.

Case	Area-1				Area-1			
	Settling Time	% Overshoot	% Undershoot	% s-s Error	Settling Time	% Overshoot	% Undershoot	% s-s Error
-25% Ttr area 1 and area 2	15.30	1.679	1.587	0.0872	12.126	0.57334	1.10415	0.0672
-25% R area 1 and area 2	15.402	1.802	1.703	0.08938	12.314	1.78542	3.07815	0.0616
Nominal Values	15.096	0.785	0.743	0.08393	10.998	0.714	1.9077	0.056
-25% Ttr area 1 and area 2	15.708	1.825	1.725	0.09156	11.844	24.69651	1.673	0.06608
-25% R area 1 and area 2	15.606	1.581	1.495	0.08938	12.482	0.49239	1.05225	0.06944

Conclusions and Future Work

In this study, we comprehensively investigated the transient and steady-state performance of a multi-source dual-area tie-line IPS with coupled AVR-LFC. It was possible to effectively regulate the IPS by using the traditional PID controller. To get the best PID tuning, a gradient-based optimizer (GBO) was used. Moreover, the suggested GBO-PID control mechanism was contrasted with the performance of several other controllers, including GBO-I-PD, GBO-TID, and GBO-I-P. Frequency deviation, tie-line power deviation, and terminal voltage responses of IPS were assessed with 5% SLP in each location. In area-1, GBO-PID generated a settling time of 0.3 s, which is 62%, 39%, and 62% better than GBO-I-PD, GBO-TID, and GBO-I-P control techniques, respectively. In area-2, GBO-PID produced a settling time of 0.2 s, which is 67%, 38%, and 58% better than GBO-I-PD, GBO-TID, and GBO-I-P control methods, respectively, in area-2 LFC. In comparison to GBO-TID and GBO-I-P control techniques, GBO-PID provided a settling time of 0.27 s in area-1 AVR, which is 35% and 42% better, respectively. In comparison to GBO-I-PD, GBO-TID, and GBO-I-P control techniques, GBO-PID provided settling times of 0.18 s in area-2, which is 34%, 42%, and 23% better, respectively. In area-2 AVR, GBO-PID provided much better overshoot response (13%, 67%, and 49%, respectively) than GBO-I-PD, GBO-TID, and GBO-I-P control techniques. Additionally, in area-1 tie-line power deviation, GBO-PID provided a better settling time response of 39%, 11%, and 47%; in area-2 tie-line power deviation, it provided a better settling time response

of 45%, 7%, and 35%. In light of this, it may be said that GBO-PID outperformed control techniques. A thorough sensitivity analysis with a 25% difference in system parameters demonstrated the robustness of GBO-PID.

The results unequivocally show that the proposed GBO-PID control methodology is superior for combined control of terminal voltage and load frequency in multi-source dual-area tie-line IPS. Future research could examine the suggested approach for concurrent control of load frequency and terminal voltage in a multi-area, multi-source IPS in the presence of nonlinearities, random loading situations, or a deregulated environment. Future research might also look into the use of GBO-PID in hybrid energy systems, including combining renewable energy sources and energy storage systems in a multi-area IPS. Examining how uncertainty and disruptions in real-time power grid conditions affect GBO-PID controller performance could be another topic for further study. Furthermore, a viable avenue for enhancing stability and performance under various operating scenarios may be the creation of adaptive GBO-PID controllers, which may make real-time adjustments based on external variables and system dynamics. Finally, a key component of future work would be extending the system to manage more intricate multi-area multi-source combinations, such as the incorporation of cutting-edge grid topologies and upcoming energy technologies like hydrogen.

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