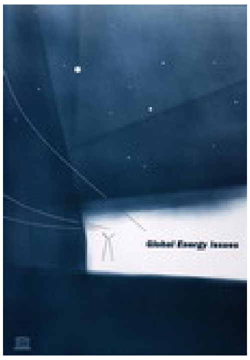

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Comparison between PID and PSO-PID controllers in analysing the load frequency control in interconnected microgrids in a deregulated environment

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Comparison between PID and PSO-PID controllers in analysing the load frequency control in interconnected microgrids in a deregulated environment

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Abstract: This paper focuses on analysing the frequency error in interconnected microgrids and reducing the generation cost, which is considered one of the objective functions. The Simulink model shows the connection between two microgrids, i.e., microgrid 1 comprises thermal, hydro and gas power plants, whereas microgrid 2 comprises thermal, nuclear and gas power plants. The change in the tie-line power is also considered while simulating the model. The paper's main aim is to reduce the variations in frequency in each microgrid to ensure the steady flow of power among the connected microgrids along with the tie-line power. Also, the robustness of PID and PSO-PID Controllers are compared and analysed. The particle swarm optimisation algorithm codes tune the controller's gains in MATLAB. The model is simulated using MATLAB 2014b, and necessary graphs are obtained, which show the frequency error reduction time in both the microgrids.

Keywords: MGs; microgrids; frequency error; LFC; load frequency control; tie-line power; PID proportional integral derivative; controller; PSO; particle swarm optimisation.

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1 Introduction

Automatic Generation Control is a very important control strategy employed by researchers all around the globe to tackle the situation of frequency errors and tie-line power flows. In a deregulated environment, Generation Companies called (GENCOs) and Distribution Companies called (DISCOs) have contracts with each other to maintain the system frequency and steady tie-line power flows (Khadidos et al., 2022). As the number of utilities is connected to the power systems or microgrids, a small change in the load can cause variation in frequency and tie-line power (Puthige et al., 2021). The operation of a microgrid includes two operating modes: Grid-connected and Islanded mode (Urooj et al., 2021). A microgrid operates in grid-connected mode when it supplies power to the main grid behaving as a current controller.The degree of supplying power to the main grid depends on the power generated within the microgrid (Urooj et al., 2021). A microgrid operates in its islanded mode when it is decoupled from the main grid and starts operating within the sources and loads (Elkabbash et al., 2021).

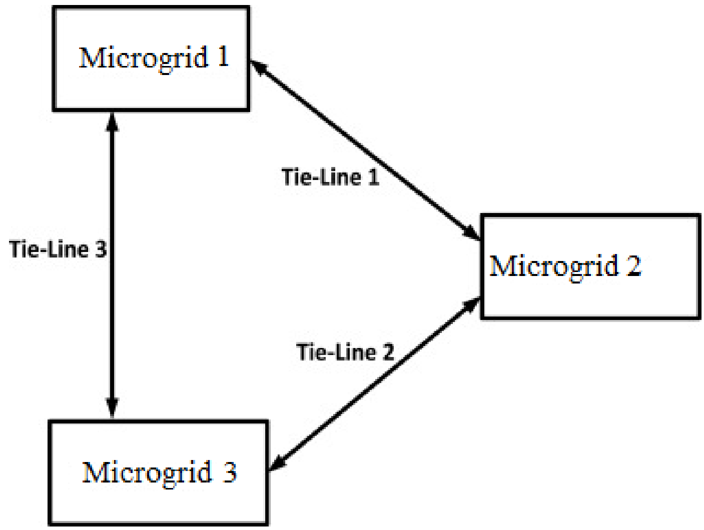
The Load Frequency Control (LFC) study in deregulated structure of 2 interconnected microgrids is presented in this paper (El-Gamal et al., 2020). The load frequency control is also called the secondary frequency control or Automatic Generation Control (AGC) (Colson and Nehrir, 2013). Load Frequency Control has many advantages in a microgrid system as it tunes and controls the frequency in interconnected areas or microgrids (Werth and Tanaka, 2015). Apart from this, it also keeps the frequency in a nominal range (Ashraf et al., 2021).

Also, the LFC helps to control electrical power interchange in interconnected microgrids (Venkatesan and Kumar, 2022). Also, LFC helps control the change in the tie-line electrical power between the interconnected microgrids. In addition, LFC keeps and controls the power output of the interconnected microgrids (Arwa and Folly, 2020).Therefore, Load Frequency Control plays a vital role in interconnected microgrids, and it can be a useful control strategy employed in the simulation of interconnected microgrids using different controllers and optimisation algorithms to reduce the frequency deviations to zero in a quick time to maintain reliability of the whole interconnected system (Ahmed et al., 2014).

Figure 1 shows the 3 Tie lines connected between 3 microgrids. Tie line power is defined as the electrical power which is generally transmitted through a common coupling between 2 interconnected microgrids to safely interchange the electrical power between different microgrids(Eisa et al., 2021). Also, if two microgrids are connected, electrical power can be transferred to any microgrid depending on the requirement of the electrical supply.

The following diagram shows that three microgrids are connected using a tie-line through which effective and safe electrical power transfer occurs.

Figure 1 Tie line power between three microgrids



The two microgrids connected through a tie line allow the electric flow among the interconnected microgrids (Ashour et al., 2021). The system frequency and tie-line power variations are monitored by the control unit and restores the common operating state of the system during critical conditions such as load disturbance.

The important components in the Microgrids are as follows:

1 *Zonal or localszed generation*: A microgrid provides different generation sources that enable the user with cooling, heating and electricity. Mainly these sources are categorised into important groups – heat/thermal energy sources (e.g., biogas or natural gas generation electrical power or micro combined heat and power) and power generation obtained from renewable sources (e.g., wind turbine power and solar power).

2 *Utilisation of electric power*: In a microgrid, many devices consume electrical energy, and thus they heat up, cool and dissipate heat in the surroundings. These sources are lighting devices and heating systems of buildings. Also, load sharing is done based on the demands of a particular microgrid.

3 *Electrical energy storage*: Electrical energy storage, in simple words, is referred to as storing electrical power. This has many advantages in ensuring frequency, voltage regulation and power quality. It also helps in smoothening the renewable energy sources output, provides power during the failure for the system and plays a significant role in optimising cost. It has important technologies, which include electrical, chemical, flywheel pressure, and technologies which stores heat (Diwedar, et al., 2019). When a microgrid consists of various energy storages with different capacities, the storage devices coordinate their charging and discharging so beautifully and effectively that tiny energy storage device does not drain out quickly

than the ones with greater capacities. This situation should be obtained under a coordinated control of energy storages based on their state of charge. Also, in an islanded mode of microgrid operation where multiple energy storage systems are used, an energy management system – EMS controls the whole system architecture.

4 *Point of common coupling (PCC)*: This is considered to be the most important parameter of the microgrid, and it is referred to as the junction in the electric circuit where one microgrid is connected to the main grid. Isolated Microgrids do not have a PCC and are generally located in remote sites like industrial sites). In this situation, the possibility of connecting with the main grid is impossible due to practical or technical limitations. A microgrid can operate in both the modes, i.e., grid-connected and standalone and manage the transition between these two. There is a contract between the main grid and microgrid in the grid-connected mode. Thus a lot of services can be provided by proper trading between this two. The real and reactive powers are generated in the islanded mode within the microgrid, which also comprises the power from the energy storage system (Venkatesan and Natarajan, 2021). With the demand in the local loads, the operating mode must be balanced. Microgrids help to stabilise the need to reduce carbon emissions by continuously providing good and efficient electric energy when the power from renewable sources is not available. Since Microgrids consists of many wires and cables, they provide more stability during harsh weather conditions and natural disasters and also provide support to the buildings or infrastructure that needs continuous maintenance following these difficult events. A microgrid always has an option of transiting in between these two operating modes in order to achieve organised maintenance, deteriorating power quality or insufficient power in the host grid, interior or exterior faults in the microgrid system locally, or for technical reasons. There are many optimisation methods that can be incorporated to improve a microgrid's energy management system's performance, economics, and flexibility. When DER units are integrated with the Microgrids, many operational challenges occur, which must be highlighted during the design of the microgrid system that provides control and protection. This will ensure that there will be no effect on the system reliability and it will not be seriously affected. This ensures that the benefits of the Distributed Generations are fully used (Tao et al., 2020).

The following points describe about the challenges faced in the microgrid system:

(a) *Reverse power flows*: The microgrid comprises of the Distributed Generation (DG) units and these units at low voltage levels give rise to power circulate in reverse direction that can lead to lot of problems including coordinating among protection units in the system, disturbed patterns of power flow, and problems in achieving voltage control.

(b) *Issues in achieving stability*: Interactions between the control systems of DG units give rise to the local oscillations, and this in turn would require analysis of the small-disturbance stability. Moreover, transient instability arises because of the transition activities of a microgrid between the two modes of operation of a microgrid. According to the recent studies, it has been found that a DC microgrid interface can eradicate the problem of stability by providing a simple control structure with smoothdistribution of electrical energy.

(c) *Use of old models*: It has been seen that the traditional use of three-phase balanced conditions is still prevailing in almost most microgrid models. The most common ones are inductive transmission lines and constant-power loads. These traditionally used models must be revised, and the microgrid structure has to be restructured or modelled again to get different optimised results.

(d) *Low inertia*: In some cases, microgrids display a low-inertia property which makes them dissimilar from huge power systems, where relatively large inertia is provided by the synchronous generators. This phenomenon is clearer if a consequential proportion of power electronic-interfaced DG units are in the microgrid. The system's low inertia has many demerits, weakens the system, and can cause severe frequency deviations in island mode operation if an appropriate control mechanism is not implemented. Synchronous generators can sometimes solve this issue as they operate at the same frequency as the grid, thus giving a damping effect on unexpected frequency variations. Other alternatives to balance the frequency include control of battery energy storage or a flywheel (Rajesh et al., 2021).

(e) *Uncertainty*: It is one of the microgrid's most important issues. The operation of the microgrids is affected by the Load profile and weather. The disturbances mentioned here make the coordination more demanding in remotely located microgrids, where the balance between demand and supply has to be maintained. Also, a failure in any of the components results in the economical operation of the microgrid. In bulk power systems, this uncertainty is higher due to the decreased loads and changes in the available energy resources.

The PID Controller evaluates and controls the error in frequency and brings it to null position quickly. Several other Optimisation techniques, like Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA), are used to tune the gains of the PID Controller to bring the frequency variations to the null position (Ali et al., 2014). The Simulink model is simulated, and necessary graphs are obtained. This paper explains the effect of the Particle swarm optimisation technique, which tunes the gains of the PID controller. When the tuned values of the PID controller are added to the simulation block, the frequency error is reduced further, and the PSO-PID controller's convergence rate is much faster than the conventional PID controller.

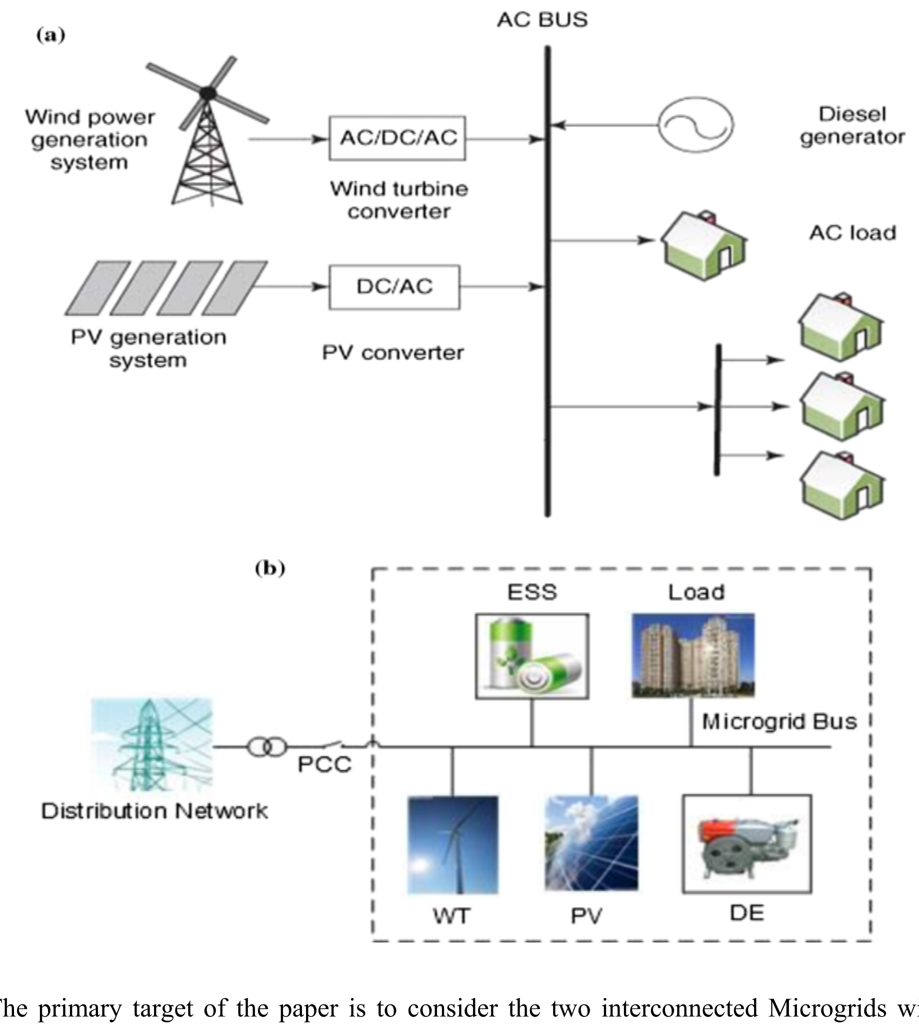
Not only is this, but the accuracy of the PSO-PID controller is also very precise. Other parameters like Area Control Error and frequency changes are calculated in order to ensure a steady power flow among the interconnected microgrids, ensuring the entire system's stability.

There are a lot of advantages of interconnected microgrids, which involve providing systematic, low-cost, and clean energy, minimising grid blockage or congestion and peak loads and providing a critical platform that raises reliability and strength (Zou et al., 2020). Apart from the advantages, there are challenges of interconnecting two microgrids that involve issues related to the quality of electric power due to the random behaviour of the renewable sources, minimising current harmonics by powering electronic devices. There are many reasons why the microgrid's reliability is affected, i.e., temporary modes of microgrid, power flow reversal in distributed energy sources, and variability in the supply and demand within the microgrid (Rana et al., 2018). There is lot of challenges other than mentioned above; the protection of microgrids is the biggest, as huge line currents can arise because of voltage sag.

Figure 2. shows the structure of a Microgrid having a Wind turbine power generation system, PV generation system, Diesel Generator (DG), and commercial and industrial loads (Dey et al., 2020).

Also, the Energy Storage devices are shown along with the Loads connected to a common coupling. Then the generated power is transferred to the distribution network. This Figure 2 shows how the generated electrical power is transmitted, and evenly distributed to the places where there is a shortage in a microgrid using different devices and systems. Also, the electrical power can be stored in Energy storage devices which can be used during electrical failure or blackout.

Figure 2 Movement of energy in a microgrid



The primary target of the paper is to consider the two interconnected Microgrids with (Thermal, Hydro, Gas) and (Thermal, Nuclear and Gas) along with the participation factors and tie-line power. The interconnections are arranged so that a minute variation in the system model can cause deviations to occur and thus affect the solidity of the power system. The observations are taken through the scope of each microgrid. Also, the frequency deviations are quickly brought to zero by tuning the gains of the controllers using PID and PSO-PID controllers. Both controllers' responses and convergence rates are noticed and recorded for observation.

The remaining part of the paper explains as follows: Section 2 explains the literature review, Section 3 explains the methodology, Section 4 explains the Simulink model and system equations, Section 5 explain the Results and Graphs and Section 6 explains the conclusion of the paper.

2 Literature review

This literature review is considered one of the most important part of the authors' research. It gives us a platform from which we get an idea of which work or research is already done in our research field and which works can be done shortly to minimise the gap between the already completed work and the work that can be completed shortly that can also become beneficial for the living community. This paper compares PSO and PSO-PID controllers, and a conclusion has been made about which controller gives the best convergence rate and results. Therefore, it becomes very important to identify the existing research work already completed by different authors all around the globe to identify the research problem and formulate it. The authors contribute to controlling frequency deviations in interconnected microgrids using different control strategies, optimisation algorithms and controllers.

Soni et al. (2019) investigated the load frequency control technique applied to two interconnected microgrids using different existing controllers. Optimisation Algorithms were employed to find the parameters of PID controllers like Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO). The work concluded settling time of frequency error in both the microgrids was observed to be very high, i.e., 12 and 18 seconds, respectively, which is very high.

Shayeghi et al. (2021) designed a controller using the technique of cascading fuzzy and control the frequency of the interconnected microgrids comprised of all renewable energy sources. They concluded that by using a multi-objective MO optimisation method, the frequency deviations were reduced to less than 6secondsbutthe convergence time was very high.

Alayi et al. (2021) investigated the Load Frequency Control (LFC) of microgrids using the improved version of the PSO algorithm, which is a specially designed Craziness-Based Particle Swarm Optimisation (CRPSO). They concluded that the microgrid frequency was reduced to zero in more than 18 seconds using PID and PI controller, but the settling time was minimised drastically to 4 seconds using CRPSO.

Regad et al. (2020), compared the performance of the Genetic Algorithm (GA) and PSO algorithms in studying the Load Frequency Control (LFC) of microgrids. They concluded that The Krill Herd technique proved economical and best collated with the GA and PSO algorithms in improving the damping performance of the frequency.

Mishra et al. (2022b) compared the performance of the Atom Search Optimization technique with Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO) to identify the Load Frequency Control (LFC) of Multi Microgrid System. They concluded that the performance of the Atom Search Optimisation technique gave a better convergence rate in minimising the frequency variations to zero in quick time.

Albogamy et al. (2022) presented a control strategy to resolve the load-shedding issue in the smart microgrid to supply consistent energy. They presented the controller which was based on a different technique having sliding mode controller that uses dynamic pricing and controls the generation of renewable energy sources. Also, the performance is compared with other existing controllers to find the effectiveness of the controllers.

Mishra et al. (2020) presented a hybrid cuckoo search and pattern search algorithm for controlling the frequency of a microgrid system. The performance of the hcsa-ps is collated with other existing controllers like GA, PSO, and the Crow Search Algorithm (CSA) algorithm.

Jagatheesan et al. (2021) studied the stabilisation of the frequency of a microgrid coupled with a thermal power system using the Gray Wolf Optimisation (GWO) algorithm. They concluded that the performance of the GWO algorithm, when compared with different existing controllers, was found more efficient and have a quick convergence rate.

Zhang et al. (2022) constructed a cluster system modelof microgrid consisting of three single microgrids to resolve the problem of economic optimisation dispatch. The model was simulated and solved by an improved butterfly optimisation algorithm, IBOA. Improving the cluster of microgrid reduced the total operating cost, the microgrid cluster's dependence on the distribution network was minimised effectively, and the expansion and implementation of renewable energy were promoted.

Thirunavukkarasu et al. (2022) presented the various EMS techniques. They disclosed that the usage of MIP-based EM solutions was the most frequent and MAS-based systems would be most perfect in resolving the critical problem of Unit Commitment (UC), Dinkelbach Method(DM) and optimisation algorithms like PSO, and methods like neural networks are best for forecasting and Economic/Environmental Dispatch. Conclusion showed that the multi-agent-based algorithms along with other existing algorithms are cheaper in cost to mark the complex Energy Management Systems and EMS problems and result in better efficiency.

Gulzar et al. (2022) presented the solutions to solve the LFC problems associated with power systems by the use various algorithms. The recent changes and modernisation in LFC structure used in different groups of renewable energy systems are explained clearly. They concluded that there is a significant need to develop the load frequency controllers with an aim to obtain solidity. The work proposed in the paper will give a lot of information about improving load frequency control of renewable energy systems.

Mishra et al. (2022a) proposed an article that improves the frequency modulation of an interconnected microgrid system by using a special controller. The uncertain behaviour of renewable energy sources along with load changes were used to identify the effectiveness of the controller. The results show that the controller propped in the paper was far more effective than the other existing optimisation algorithms.

Kandasamy et al. (2022) proposed an article that focuses on enhancing the transient stability of an interconnected microgrid system by the effective use of Automatic Load Frequency Controllers (ALFC) technique by minimising its frequency deviations. The effectiveness of ALFC for interconnected microgrids is modelled using MATLAB/ Simulink considering changes in system parameters and load. The conclusion of the paper validates the performance of the controller.

Fayek and Rusu (2022) presented different techniques to solve both load frequency control and automatic voltage regulation of two interconnected microgrids. The renewable energy sources like solar and bio energy operates the two microgrids. The parameters of the controller were regulated and the results show that the use of LFC-AVR technique proved far better than existing designs.

Babaei and Hadian (2022) used methods for maintaining balance and keeping the frequency deviation under nominal range. He proposed a learning-based fractional-order controller in order to reduce and regulate the variations in frequency of microgrids, including micro-turbines, photovoltaic panels and wind turbines, to enhance the system performance and minimising frequency variation time. The performance of the proposed controller was better than other existing conventional methods used in the simulating the microgrid systems.

Doan et al. (2022) proposed a technique to minimise the frequency deviations using the process of tuning the parameters of PID controller using Particle Swarm Optimisation (PSO) technique. He considered a hydraulic station, a non-reheat plant, a reheat unit, and RE sources such as wind and solar power to simulate the model in MATLAB. The conclusion proved the effectiveness of the proposed controller with better results. This section shows the existing research work done by authors across the globe, and it gives a clear idea of moving forward with the works which can still be implemented. Thus, this paper focuses on the works other authors have failed to achieve.

3 Methodology

The methodology used in this paper is the effect of PID and PSO-PID Controllers in bringing the system frequency to zero in a quick time. Also, the codes of the PSO Algorithm are written in MATLAB mfile that helps to regulate and update the PID controller gains.

Elmer Sperry developed the first PID controller in the year 1911. The first pneumatic PID controller came into effect in 1940, using a derivative action to minimise overshooting problems (Lee et al., 2015). Ziegler & Nichols, in the year 1942, brought rules to find and set the appropriate parameters of PID controllers for the engineers (Cai and Hu, 2019; Loh et al., 2013). Lastly, automatic PID controllers were enormously used in industries in the middle of the year 1950.

Figure 3 clearly indicate how the parameters of the PID controller are represented as transfer function blocks. The equation is formulated below. It shows the gains of the P, I & D controllers separately in the form of an equation where $u(t)$ is considered as the output control variable of the controller (Thirugnanam et al., 2021; Xu et al., 2020). The variable $e(t)$ is considered as the error value, which the PID Controller tunes.

$$u(t) = K_p\, e(t) + K_i \int E(t)\,dt + K_p \frac{de}{dt} \tag{1}$$

3.1 P-controller

The Proportional or P-controller produces an output equivalent to the current error e(t).This controller collates the required or set point with the actual or feedback process value. The proportional constant is multiplied with the final error in order to obtain the output from the controller. The controller output depends on the error value, i.e., the output will be at null position if the error value is equal to zero.

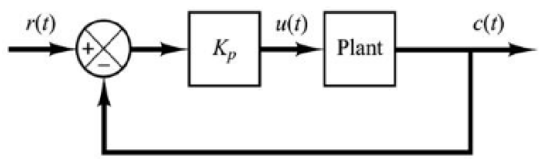
Figure 4 shows the transfer function blocks of the P-controller. It shows the gains of the P-controller in the form of an equation where c(t) is considered as the output control variable of the controller (Zhou et al., 2020; Alam et al., 2020). The Variable r(t) is the error value, which the PID Controller tunes.

Figure 3 Representation of the transfer function blocks of PID controller

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_p \frac{de}{dt}$$

$u(t)$ = PID control variable
K_p = proportional gain
$e(t)$ = error value
K_i = integral gain
de = change in error value
dt = change in time

Figure 4 Representation of the transfer function blocks of the P-controller

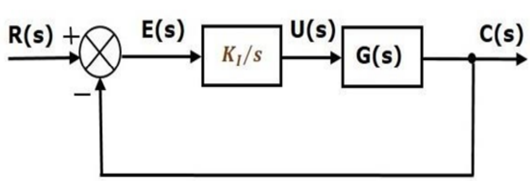


3.2 I-controller

The I-controller plays a vital role in eliminating the error when the P-controller fails to achieve it. P-controller has a limitation as there exists a difference in the process variable and set point.

Figure 5 shows the function blocks of the I-controller. It shows the gains of the I-controller in the form of an equation where C(s) is considered as the control variable in the output side of the controller (Daneshva et al., 2021; Zhou et al., 2020).

Figure 5 Representation of the transfer function blocks of the I-controller



The Variable E(s) is considered as the error value, which the PID Controller tunes.

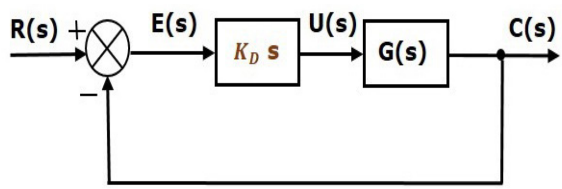
3.3 D-controller

The I-controller cannot predict the future behaviour of the error, and behaves normally once the set point is changed. The D-controller controls this issue by predicting the future behaviour of the error. The output of the D-controller is given below:

(Rate of change of error to time) × (derivative constant)

Figure 6 clearly indicates the transfer function blocks of the D-controller. It shows the gains of the D-controller in the form of an equation where C(s) is considered the controller's output control variable (Lai et al., 2021; Sivaranjani et al., 2021). The Variable E(s) is the error value, which the PID Controller tunes.

Figure6 Representation of the transfer function blocks of the D-controlle

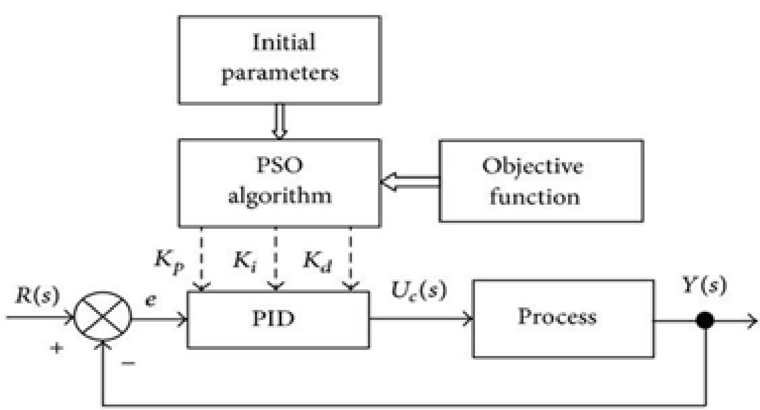


3.4 PSO-PID controller

The Particle Swarm Optimisation algorithm modulates and fine-tunes or regulates the gains of the PID controller to quickly bring the frequency deviations to zero. The PSO optimisation codes are formulated in the MATLAB function file, and the best solutions for the gains of P, I and D are obtained, which are then fed into the PID controller to obtain the necessary graphs. Figure 7 clearly indicates the formulation of the pattern or flow of the PID controller based on the PSO algorithm. It shows that first; we need to initialise the parameters along with the objective function that needs to be tuned by the PSO Algorithm (Yang et al., 2021).

The gains of the P, I and D are tuned and fed to the PID controller to reduce the frequency deviations to zero.

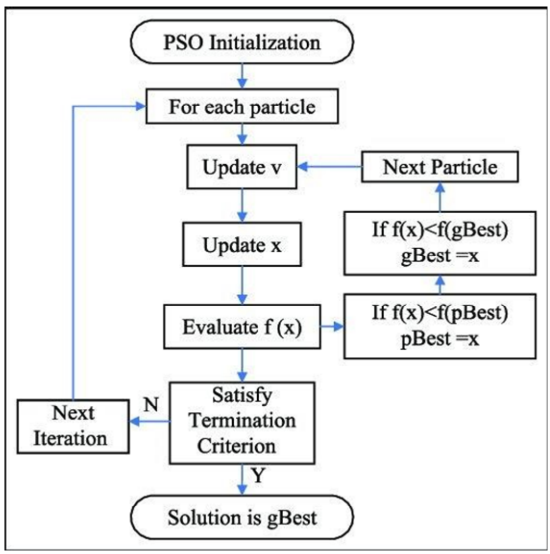
Figure7 PSO-based PID controller design



PSO algorithm is an approach that was suggested and put forward by Kennedy and Eberhart. It is a universal approach for optimising that is formulated because the imagination of social activities in the group of birds and schools of his hand is broadly applied in numerous engineering problems due to its high arithmetical efficiency (Singh et al., 2021a, 2021b).

Figure 8 shows the basic steps involved in the flowchart of the PSO Algorithm. It shows that every particle updates its velocity and position in search of food by the groups of birds, and the updated values are known as their best values compared to their previous values (Dissanayake and Ekneligoda, 2021).

Figure 8 Flowchart of PSO algorithm



The function *fx* is evaluated, and if this value is less than the best values (PBest), it is printed as the best value. Also, the process continues for the next particle, and the algorithm continues till the termination criteria are satisfied. Finally, the best solution is taken as the final value.

The number of variables and parameters assigned in the PSO algorithm is less than the other optimisation algorithms. In the PSO technique, a set of artificial birds is taken as the reference with random positions and velocities. Each bird in the group is dispersed all around the search space at the early searching stage (Rosso et al., 2021). Each particle in the group modifies or alters its position and velocity to achieve the objective function, its flying adventure or experience, and its companion's. In the final stage of the optimisation search, every particle computes its best position, known as pbest and secures the global best position statistics attained by any particle in the swarm, known as gbest.

The PSO concept upgrades the velocity of each particle at each instant of time in relation to the best position discovered by the particle and the best position found by the neighbourhood. If we consider the search space as *d*-dimensional, the current position of the particle in the search space can be shown by vector $X_i = (x_{i1}, x_{i2}, ..., x_{id})$', the best position of the particle until then, i.e., its cognitive memory can be shown by $P_i = (p_{i1}, p_{i2}, ..., p_{id})$', and at last the velocity of the particle is written as $V_i = (v_{i1}, v_{i2}, .., v_{id})$', Also, '$g$' is defined as an index to the best particle in the group, upgrading the position and velocity at every iteration is made by the following equations.

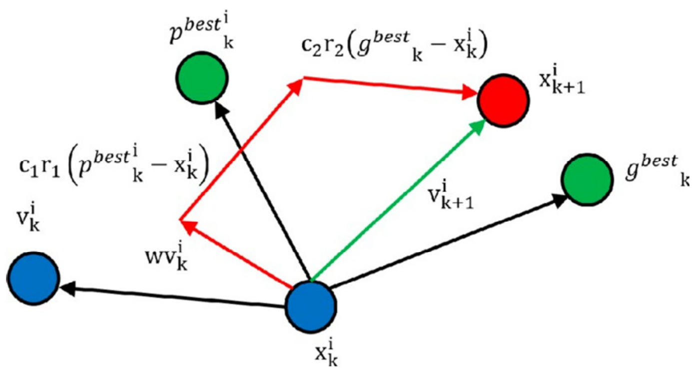
$$v_i^{k+1} = wv_i^k + c1r1(p_i^k - x_i^k) + c2r2(p_g^k - x_i^k) \tag{2}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{3}$$

'w' is the inertia weight; c_1, c_2 are considered as two positive constants called cognitive and social coefficients, respectively; r_1, r_2 are considered as the random numbers of the interval [0, 1] produced at every iteration of the algorithm, for each particle in each dimension; and $k = 1,2,\ldots$, defines the total number of iterations (Singh et al., 2021a, 2021b).

Figure 9. shows the values of the parameters of position and velocity that get updated in the swarm in search of the best solutions individually and globally (Sousa-Ferreira and Sousa, 2017). Every time the particle updates its position and velocity in search of the best position as compared to the previous one.

Figure 9 The updating position and velocity values of the (PSO) algorithm



4 Simulink model and system equations

The Simulink model of interconnected microgrids in a deregulated environment is constructed in MATLAB 2014b by taking IEEE standards into account, shown in Figure 10. The Disco Participation Matrix (DPM) is also formulated along with tie-line power, which is fed to the two microgrids. The dynamic responses of Δf1, Δf2 and ΔPtie 1–2 are obtained after simulating, and necessary graphs are plotted.

DISCOs and GENCOs contract with each other in a deregulated system to meet the demand for electrical power in emergencies. The following matrix called Disco Participation Matrix (DPM) gives us the clear idea of the concept associated with the contracts. The columns in DPM represent the total number of DISCOs, and the rows represent the total number of GENCOs in the system. Each matrix element represents a little of the total load contracted by a DISCO toward a GENCO. The addition or total of a column's elements in the DPM is equal to1.

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix}$$

where

cpf means contact participation matrix.

cfp_{ij} represents the general participation factor

where

cpf means contact participation matrix.

cfp_{ij} represents the general participation factor

where

i= participation factor of GENCO

j= participation factor of load DISCO

$$\sum_{i=1}^{n} cpf_{ij} = 1 \tag{4}$$

where

The total of every value or entry in a column in the matrix is one or unity.

Equation (5) clearly indicate the participation factors (apf) of area control error and they are the coefficient factors that spread the ACE among GENCOs. If '*m*' is taken as the number of GENCOs, then

$$\sum_{i=1}^{m} apf_i = 1 \tag{5}$$

The following equation show the scheduled value of steady-state tie-line power as:

$\Delta Ptie_{1-2}, scheduled$ = (Demand of DISCOs in microgrid 2 from GENCOs in Microgrid1)–(Demand of DISCOs in Microgrid1 from GENCOs in Microgrid 2).

The following equation show the tie line power error $\Delta Ptie_{1-2}, error$ as:

$$\Delta Ptie_{1-2}, error = \Delta P_{1-2}, actual - \Delta P_{1-2}, scheduled$$

In Figure 10, the Simulink model is based on the IEEE standards, where two microgrids are interconnected. Also, the frequency deviations are minimised to zero using PID and PSO-PID controllers. The sub-system model is formulated, which details the change in the generated power. This model has a block named Microgrid 1 in which thermal, hydro and gas power plants are interconnected. Another block named Microgrid 2 consists of thermal, High Pressure (HP), Low Pressure (LP) turbines and gas power plants. There is a sub-system Block consisting of all the equations related to the change in the power and cost. This figure shows the main block of the whole system.

$\Delta Ptie_{1-2}, error$ is used to find the ACE signals and not $\Delta Ptie$, which is found in traditional power systems.

$$ACE_1 = B_1 \Delta f_1 + \Delta Ptie_{1-2}, error \tag{6}$$

$$ACE_2 = B_2 \Delta F_2 + \Delta Ptie_{1-2}, error \tag{7}$$

The tie line power is expressed as follows:

$$\Delta Ptie_{12} = (\Delta f 1 - \Delta f 2) \tag{8}$$

Figure 10 IEEE-based AGC model in a deregulated environment

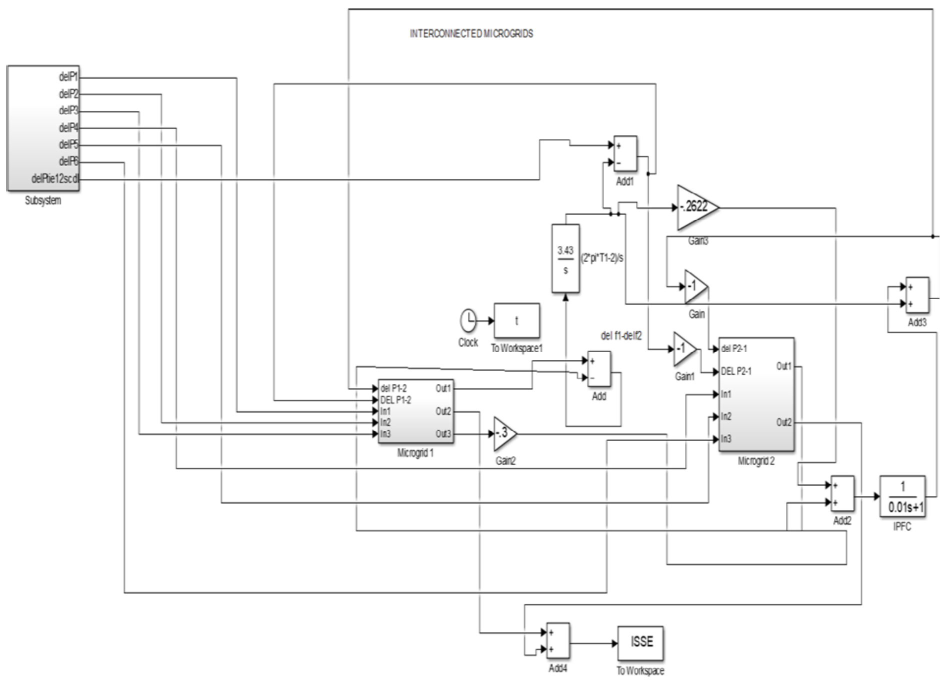
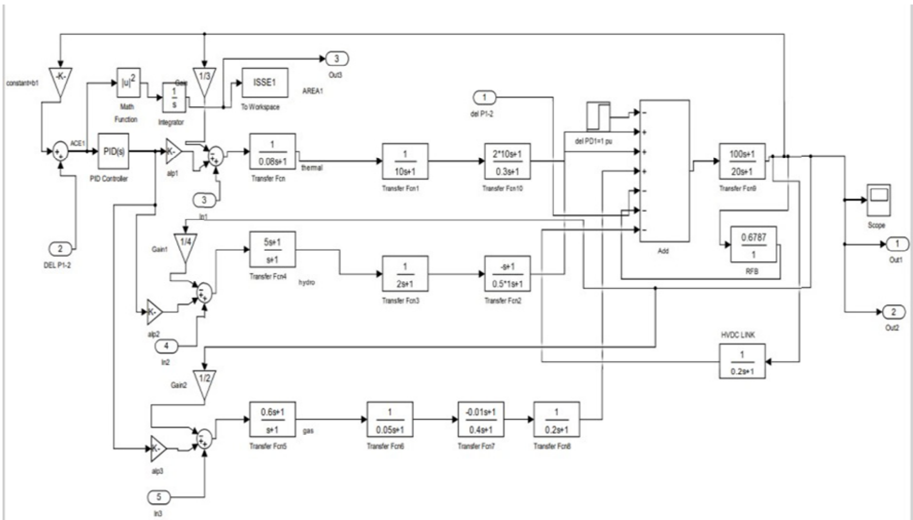


Figure 11 shows the sub-system model of Microgrid 1, which comprises thermal, hydro and gas power plants. The transfer function blocks of the power plants are formulated and arranged in the Simulink along with the loads and power system transfer function. The PID controller controls the error in the form of frequency variations. Also, the frequency deviations are observed in the scope. The gains of the PID controller are regulated by the PSO Algorithm codes written in MATLAB function file.

Figure 11 Sub-system model of Microgrid 1



The following equation shows the tie line scheduled power taken from Microgrid 1to Microgrid 2 is

$$\Delta Ptie_{1-2},\ scheduled = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj} \tag{9}$$

The following equation helps to calculate the Integral of time-weighted absolute error of frequency, ITAE:

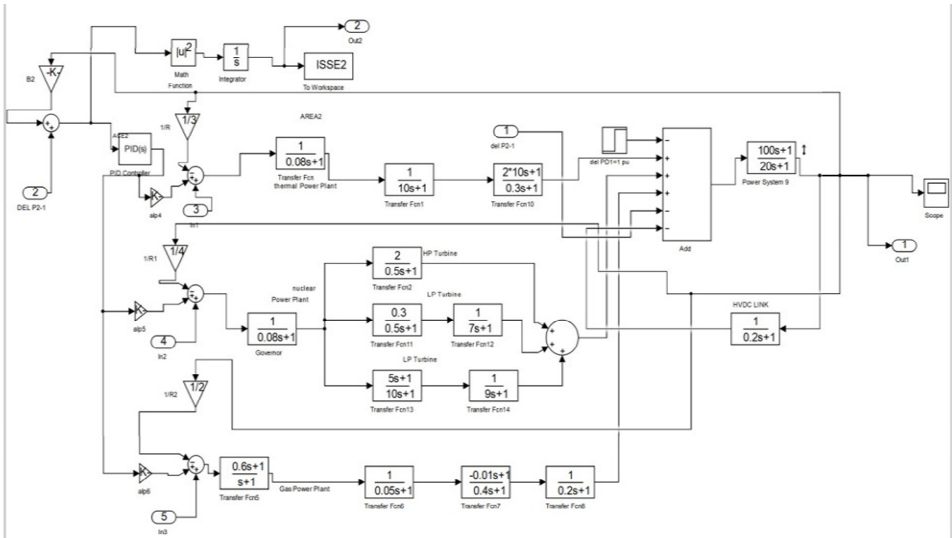
$$M = ITAE = \int_{0}^{t_{sim}} |\,\Delta f\,|\,.t.d \tag{10}$$

J is considered the objective function or Integral Time Square Error (ITSE), which needs to be minimised using the PSO algorithm.

$$J = \int_0^t \left(\Delta f_1^2 = \Delta f_2^2 + \Delta p_{tie1-2}^2\right) tdt \tag{11}$$

Figure 12 shows the sub-system model of microgrid two, which comprises thermal, High Pressure (HP), Low Pressure (LP) turbines and gas power plants. The transfer function blocks of the power plants and turbines are formulated and arranged in the Simulink along with the loads and power system transfer function. The PID controller controls the error in the form of frequency variations. Also, the frequency deviations are observed in the scope. The gains of the PID controller are regulated by the PSO Algorithm codes written in mfile.

Figure 12 Sub-system of Microgrid 2



5 Results and graphs

This section gives the information about the results and graphs attained after simulating the model in MATLAB. The PID controller controls the frequency variations in both the microgrid systems and the tie line power is kept in a nominal range. The PSO-PID controller helps to tune the PID controller gains, and the tuned values of KP, Ki and Kd in both the microgrids bring the frequency variations to zero quickly.

Table 1 shows the P-, I- and D-values of the PID controller in Microgrid 1. Also, the frequency deviation error reducing time is shown. These values are obtained by tuning the whole system using a PID controller. The PID controller tunes the whole system; thus, the best values are obtained, bringing the frequency deviations to zero. Also, it is observed that the frequency error in Microgrid 1is reduced by 9 seconds.

Table 1 Values of P, I and D and Δf_1 in Microgrid 1

Value of P	–1.36694293828293
Value of I	–1.44237955338477
Value of D	–0.3
Frequency Error v Δf_1	9 seconds

Table 2 shows the P-, I- and D-values of the PID controller in Microgrid 2.Also, the frequency deviation error reducing time is shown. These values are obtained by tuning the whole system using a PID controller. The PID controller tunes the whole system; thus, the best values are obtained, bringing the frequency deviations to zero. Also, it is observed that the frequency error in Microgrid 2 is reduced by 10 seconds.

Table 2 Values of P, I and D and Δf_2 in Microgrid 2

Value of P	2.39297691363595
Value of I	2.19525701555697
Value of D	0.0466551544867353
Frequency Error Δf_2	10 seconds

Table 3 clearly indicates the values of the gains of the PSO-PID controller after running the PSO algorithm in MATLAB. These values of the PID controller are obtained from running the simulation mfile codes for the PSO Algorithm. The codes of the PSO Algorithm are formulated in MATLAB, and then the system is made to run. These codes automatically regulate and adjust the gains of the PID controller and select the best values of P, I and D, shown in Table 3. The gains of both the PID controllers in Microgrid 1 and Microgrid 2 are shown. When these tuned values are fed to both the controllers in Microgrid 1 and Microgrid 2, the frequency error is brought to zero quickly.

Table 3 Values of gains of PSO-PID controller in Microgrids 1 and 2

	Microgrid 1	*Microgrid 2*
Valueof Kp	Kp1 = 0.5260	Kp2 = 1.7225
Valueof Ki	Ki1 = –0.3394	Ki2 = 3.4335
Valueof Kd	Kd1 = 0.1463	Kd2 = 0.0022

Figure 13 shows the frequency error in Microgrid 1using the PSO-PID controller. The frequency error is considered along the *y*-axis, and the time along the *x*-axis. The PID controller gains obtained by the PSO Algorithm were incorporated into the controllers, and the system was run. The simulation result shows that the frequency error in Microgrid 1 was reduced to zero in 7 seconds. The graph shows that the error has a peak at the start, and then it settles to zero. Thus the solidity of the system was maintained, and a smooth circulation of electrical supply was enabled through the tie-line.

Figure 13 Frequency error Δf1 in Microgrid 1 using PSO-PID controller

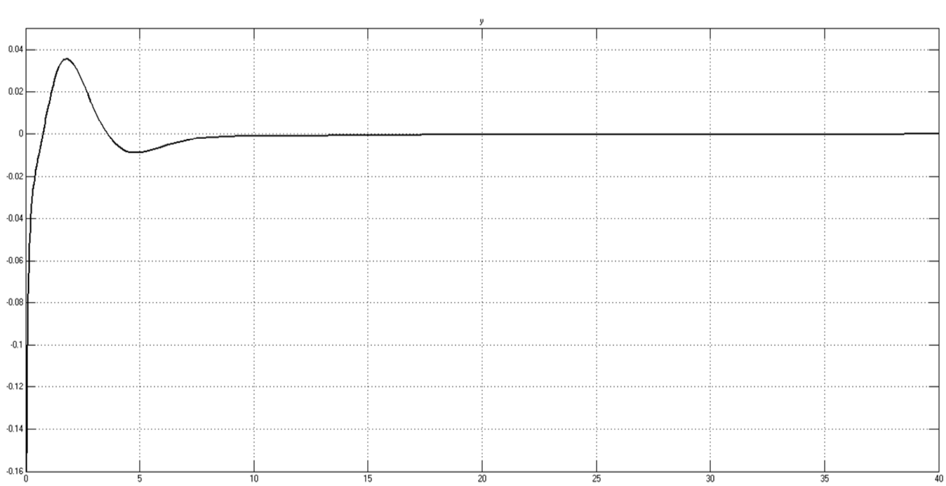


Figure 14 shows the frequency error in Microgrid1usingthe PID controller. The frequency error is considered along the *y*-axis, and time along *x*-axis. The PID controller tuned the system and obtained the frequency minimisation curve. The simulation result shows that the frequency error in Microgrid 1 was reduced to zero in 9 seconds. The graph shows that the error has a peak at the start, and then it settles to zero. Thus, the system's solidity was conserved, and a smooth circulation of electrical supply was enabled through the tie-line.

Figure 14 Frequency error Δf1 in Microgrid 1 using PID controller

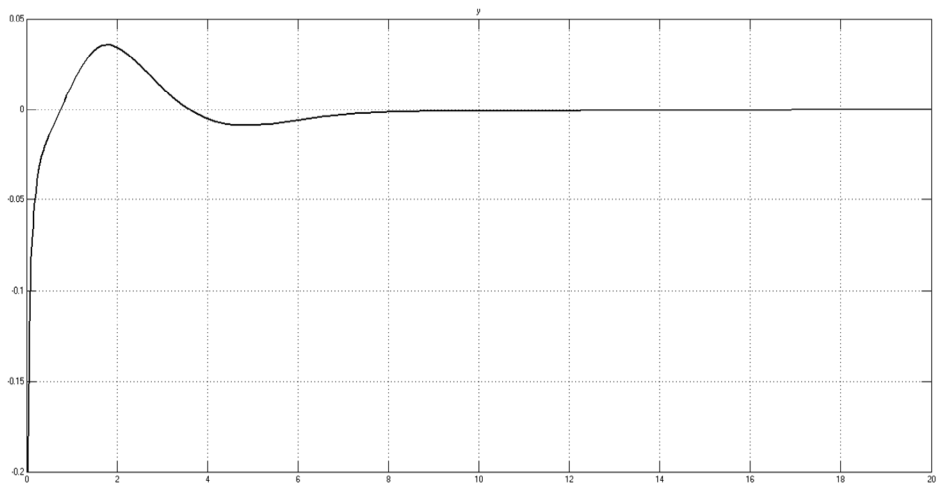
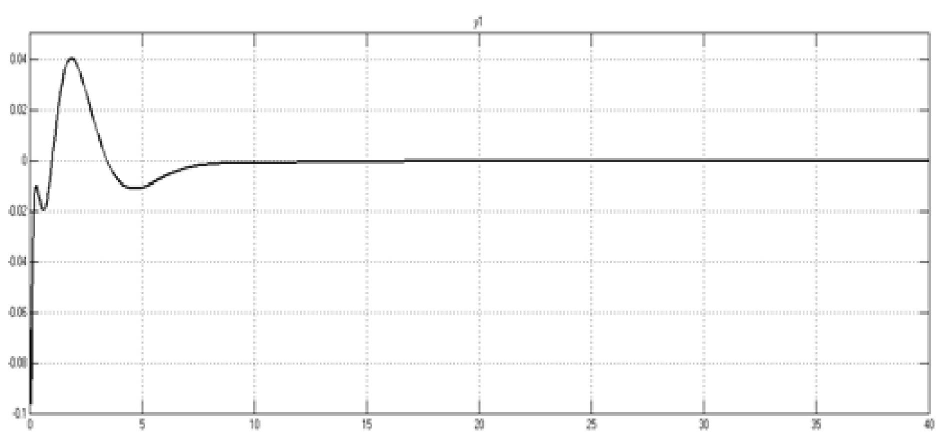


Figure 15 clearly indicate that the frequency error in Microgrid 2 using the PSO-PID controller. The frequency error is considered in the *y*-axis, and the time in the *x*-axis. The PID controller gains obtained by the PSO optimisation Algorithm were incorporated into the controllers, and the system was run.

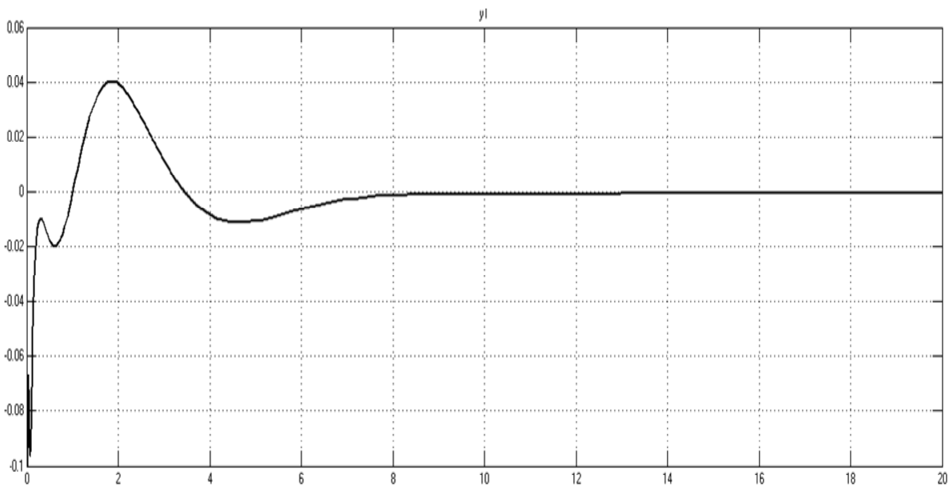
Figure 15 Frequency error Δf2 in Microgrid 2 using PSO-PID controller



The simulation result shows that the frequency error in Microgrid 2 was reduced to zero in 6 seconds. The graph shows that the error has a peak at the start, and then it settles to zero. Thus the solidity of the system was maintained, and a smooth circulation of electrical supply was enabled through the tie-line.

Figure 16 clearly indicate that the frequency error in Microgrid 2 using the PID controller, which is brought to zero in 10 seconds. Since the system is very complex, it takes a few seconds for frequency deviations and Area control errors in 2 microgrids to settle to the null position. The PID controller tuned the system and obtained the frequency minimisation curve. The simulation result shows that the frequency error in Microgrid 2 was reduced to zero in 10 seconds. The graph shows that the error has a peak at the start, and then it settles to zero. Thus the solidity of the system was maintained, and a smooth circulation of electrical supply was enabled through the tie-line.

Figure 16 Frequency error Δf2 in Microgrid 2 using PID controller



The frequency variations in the interconnected microgrids are brought to the null position, 0, quickly in seconds. Suppose these frequency variations stay in the system for a longer time. In that case, they can damage the system's stability and thus degrade the electrical power supply transfer between the interconnected microgrids. So the foremost objective is to bring the frequency variations to zero in as much less time as possible to maintain the solidity of the whole model system.

In order to maintain the solidity of the system, focus should be on keeping the frequency deviations and Area control error under the nominal range, i.e., less than 5 seconds, because if frequency deviations are not minimised quickly, then it can lead to the total shutdown of the system resulting in total black. Frequency deviation or error is the mismatch between the power generation in a particular microgrid and the electric power demand in that particular microgrid. This gives rise to the error in frequency or deviation in the frequency in a particular microgrid. Even if one parameter does not equal the other, frequency error exists. So frequency error for Microgrid 1is referred to as the frequency deviation in Microgrid 1, and the frequency error for Microgrid 2 is referred to as the frequency deviation in Microgrid 2. This frequency error must quickly be brought to zero to maintain stability. It is observed from the above graphs that the PSO-PID controller gives finer execution than the conventional PID controller in terms of minimising the frequency deviations. It is noticed that the frequency error in Microgrid 1 is minimised in 7 seconds by the PSO-PID controller, whereas it is minimised in 9 seconds by the PID controller. Also, the frequency error in Microgrid 2 is minimised in 6 seconds by the PSO-PID controller, whereas it is minimised in 10 seconds by the PID controller. These results show that the PSO-PID controller is fast, efficient, and has a quicker convergence rate than the PID controller.

6 Conclusion

This paper shows the modelling of 2 interconnected microgrids under deregulated environment considering the bilateral contracts of Distribution companies DISCOMs to reduce the frequency deviations and area control errors in each microgrid. The paper's outcomes are as follows: The system is modelled in MATLAB 2014b following the IEEE Standards. The bilateral contracts and the tie line power error are considered and fed to the interconnection network between 2 microgrids. The PSO-PID controller in each microgrid tunes the system error while the simulation runs on MATLAB 2014b. The PSO-PID controller and PID controller help quickly bring the system frequencies and errors in each microgrid to the null position. The results from the graphs indicate that the PSO-PID controller is far superior than the PID controller in quickly bringing the frequency deviations to the null position. The graphs from the simulation show that the frequency deviations are reduced by 7 seconds in Microgrid 1 and 6 seconds in Microgrid 2 using PSO-PID controller. Also, the graphs indicate that the frequency deviations are reduced by 9 seconds in Microgrid 1 and 10 seconds in Microgrid 2 using the PID controller. In this study, the superiority of the PSO-PID controller over the conventional PID controller was proved. Many other existing optimisation algorithms are capable of tuning the gains of the controllers and bringing the system frequency to null position quickly. A lot of research can be done in this field by selecting an appropriate optimisation algorithm that can quickly reduce the frequency deviations and area control errors to the null point.

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Abbreviations

- LFC: Load Frequency Control
- MG: Microgrid
- DISCOM: Distribution Company
- ACE: Area control error
- DPM: Disco participation matrix
- PV: Photovoltaic
- PSO: Particle Swarm Optimisation
- PID: Proportional Integral Derivative