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# Blackout in Power Systems: Research on Frequency Control using Flower Pollination Algorithm

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**Abstract** - Ensuring the continuous provision of electricity to meet escalating demands hinges on the stability and dependability of power systems. Essential to this stability is the precise control of frequency, which acts as a critical regulator, ensuring equilibrium between power generation and consumption and averting the frequency variations that may culminate in power outages. This study delves into the novel application of the Flower Pollination Algorithm (FPA) as a means to augment frequency control within power systems. Specifically, this paper puts forth an analysis of a proportional integral derivative controller grounded in the Flower Pollination Algorithm. This analysis is geared toward addressing the control challenges associated with load frequency during emergency situations, with the ultimate goal of averting blackouts within a multi-area control framework. One of its most severe glitches is the power outage, a terrible occasion that may disturb a significant segment of the system, playing destruction to human and causing incredible financial misfortunes. Accordingly, understanding the systems prompting power outages and making a consistent and flexible power network has been a significant issue, drawing in the consideration of researchers, designers, and partners. The control techniques show the effective capacity of the quick reaction energy storage structure in forestalling and anticipating power outages in smart grids. The Internal Model Control Proportional Integral Derivative Flower Pollination (IMC-PID FP) technique is introduced with the assumption of decoupled tie-line power flows, offering a versatile controller with a straightforward structure that holds potential for practical control systems. This proposed method undergoes testing within various operational scenarios of a three-region power system, aiming to demonstrate the improved outcomes of the IMC-PID controller based on the Flower Pollination Algorithm (FPA).

***Key words:*** PID controller, load frequency control, flower pollination algorithm, three area power system.

## 1. Introduction

The quality of power generation hinges on load frequency control, a vital function that governs both the system frequency and inter-area tie-line power. To ensure a consistent and high-quality power supply, load frequency control must exhibit resilience in the face of unforeseen external disruptions and variations in power system parameters. To address the need for robust load frequency control in single-area, single- or multi-source power systems, we have designed PI-PD controllers known for their ability to withstand parameter fluctuations and effectively suppress disturbances. The design process involved utilizing the stability boundary locus of the closed-loop control system, applying the weighted geometric centre approach to determine the optimal settings for the PI-PD controllers. This strategic approach was sequentially implemented for both the inner and outer loops within the PI-PD control system.

Load frequency control (LFC) is the fundamental significant perspectives in power framework. It reflected as a direct demonstration for the essential limitation accomplishment in power network for variation both load and generation side. Control deviations and reproductions are achieved for three situations for different operating circumstances for huge load request. Any variation in frequency occurred because of any befuddle between the load and generation. Automatic generation control makes adjust among burden load and generation. Two-area deregulated control framework is considered with Batteries in both the territories. With a traditional Proportional Integral (PI) controller, it is hard to get the ideal results. Henceforth, canny strategies are used to adjust the PI controller of the load frequency control to mend the dynamic outcome [1, 2].

Scheming the frequency and tie-line power deviation for various loading situations Self tuning fuzzy PID [3], Unified PID design [4], genetic algorithms [5], Gaussian based discrete [6], Fuzzy logic controller are used. It is tracked down that the system reaction with Fuzzy logic controller better in contrast with the reaction with PID controller for single-zone just as two-area [7-9].Several algorithms are used to improve the frequency and tie-line power deviation of multi area power system. Biogeography-based optimization (BBO) algorithm calculation is used to tune regulator boundaries. An alternate sort of methodology is made to plan a multi-area, which contains weighted function. The issue of Load Frequency Control (LFC) in a multi-territory power system under liberated conditions is a significant concern, and the approach of choice for designing local load frequency controllers is the Internal Model Control PID method. The stability of a decentralized LFC framework can be effectively assessed, as has been documented [10-12]. A Coefficient Diagram Method (CDM) has been introduced specifically for an interconnected decentralized LFC setup. This proposed strategy underwent testing in both two and three-control region power systems, considering various scenarios involving load changes and boundary alterations. Nevertheless, it's worth noting that the proposed CDM proves to be more practical in terms of load estimations, especially when compared to the capabilities of model predictive controllers (MPC) [14,15]..

The time-subordinate dormancy can trigger fast frequency varieties, which have become primary concerns in power framework steadiness. Information driven technique is proposed to appraise the time-subordinate latency in the system dependent on the frequency slope of an expected model of the system [16-17].A two region thermal system with dead-band nonlinearity is considered with Flower Pollination (FP) weighted execution capacities technique, it requires less exertion to acquire the loads for multi target work. Anonlyone run of the proposed procedure yields both ideal loads and global least [18]. FP is applied in AGC for synchronous improvement of a few additions and different boundaries. An endeavour has been made to apply PI-PD course regulator without precedent for Automatic Generation Control (AGC). Sensitivity examination of the ideal additions acquired at normal conditions and boundaries uncovers that they are robust and need not be reset for wide changes in framework conditions and parameters [19]. Cuckoo Search beats PSO, GA in taking care of LFC issue because of just a single boundary needed to fine-tune. PSO experiences powerless nearby inquiry capacity and the calculation may prompt conceivable capture in neighbourhood least arrangements. The ability of the created regulators to make up for the correspondence time postponement and protect its acceptable presentation is illustrated [21, 22].

Highly Robust Observer Sliding Mode (HROSM) illustrates excessive performance and high strength against outside unsettling influences regarding overshoots and settling time for interrelated power systems [23].The similar outcomes uncover the incomparability of the FO-3DOF-TID controller over its different partners regarding damping scheme fluctuations [24-26].Flower Pollination Algorithm with Internal Model Control- Proportional Integral Derivative is proposed to improve the performance of frequency control and blackout over multi area. Multi-objective Golden Flower Pollination Algorithm (MOGFPA) is a meta-heuristic hybridised version that has been shown to be the most effective way for selecting the best reconfiguration for distribution networks. The load balance index is another statistic in addition to power losses. Real and reactive indices are used to formulate the formulation for the load balance index. Power losses and the load balance index become the primary parameters that need to be optimised for the multi-objective distributed generation placement and distribution network routing [27-29].

In the context of a multi-area power system, especially within a deregulated environment, effective and cost-efficient coordination of online generation facilities is of utmost importance. Economic load dispatch for multi-area systems has become a critical service due to economic and environmental considerations, as outlined in references [30-32]. The primary objective is to optimize generation levels and facilitate cross-border energy trading among neighbouring regions while adhering to operational and physical constraints. There are two primary approaches for addressing the economic load dispatch problem in multi-area systems: centralized and decentralized methods. In a centralized approach, a central coordinator is responsible for selecting the optimal settings for the entire network. In contrast, decentralized techniques involve breaking the network into multiple independent sub-units [33-35].

The widespread adoption of distributed generators made from renewable energy sources has caused a paradigm change in power systems [36]. The current power system is heavily integrated with wind turbines and solar photovoltaic panels primarily to support green initiatives in the electrical energy sector. However, integrating these renewable energy sources destabilizes the frequency of the modern power system [37-39]. Due to the lower inertia and complicated regulation of power electronic converters used in renewable energy conversion systems, the frequency control has not received enough attention to date [40-43]. To maintain the dependable operation of an islanded interconnected micro-grid system, a dual-stage frequency control method is suggested. The controller assists the micro-grid in frequency stability and upholds load-demand balance under atypical operating circumstances [44]. The efficient use of power and preservation of supply and demand equilibrium can both be achieved with the help of intelligent energy management and control systems. The modelling of a decentralised energy management system is suggested in this research as a means of lowering system operating expenses when load and renewable generation uncertainties are present [45-47].

Optimized tilt-integral double derivative controller for multi-area load frequency control using the bird swarm technique. Each section of the proposed system has a single thermal and realistic dish-Stirling solar thermal system unit [48]. As an additional controller, the tilt-integral-double derivative controller, an unique controller, has been developed. It has been successful to optimise the controller and other parameters using the bird swarm technique [49]. In terms of peak overshoots, undershoots, and settling time, the system with the suggested tilt-integral-double derivative controller beat those with proportional-integral-derivative, tilt-integral-derivative, and tilt-integral-double derivative controllers [50].

## 2. Design of LFC in deregulated environment

The Augmented Generation Participation Matrix (AGPM) consists of rows and columns, with the total number of rows and columns matching the overall count of GENCOS (generating companies) and DISCOS (distribution companies) within the entire power system. Within this matrix, the Generation Participation Factor (GPM) signifies the contribution of a specific GENCO to the overall capacity, which influences the subsequent requirements of DISCO j, based on established agreements and feasible protocols. The concept of AGPM is employed to represent the potential contractual arrangements.

$$GPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \quad (1)$$

Where, The AGPM shows the investment factor of a GENCO in the heap following agreement with a DISCO. An AGPM for a enormous scope power system with N control area has the accompanying structure of the following.

$$AGPM_{ij} = \begin{bmatrix} gpf_{(x_i+1)(z_j+1)} & \cdots & gpf_{(x_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(x_i+n_i)(z_j+1)} & \cdots & gpf_{(x_i+n_i)(z_j+m_j)} \end{bmatrix} \quad (2)$$

Given the presence of multiple GENCOS within each region, the allocation of the ACE sign is necessary, considering their respective expertise and participation factors in the AGC task. To evaluate the effectiveness of the proposed control method, we use the three-control-area power system depicted in Figure 1 as a representative test system.

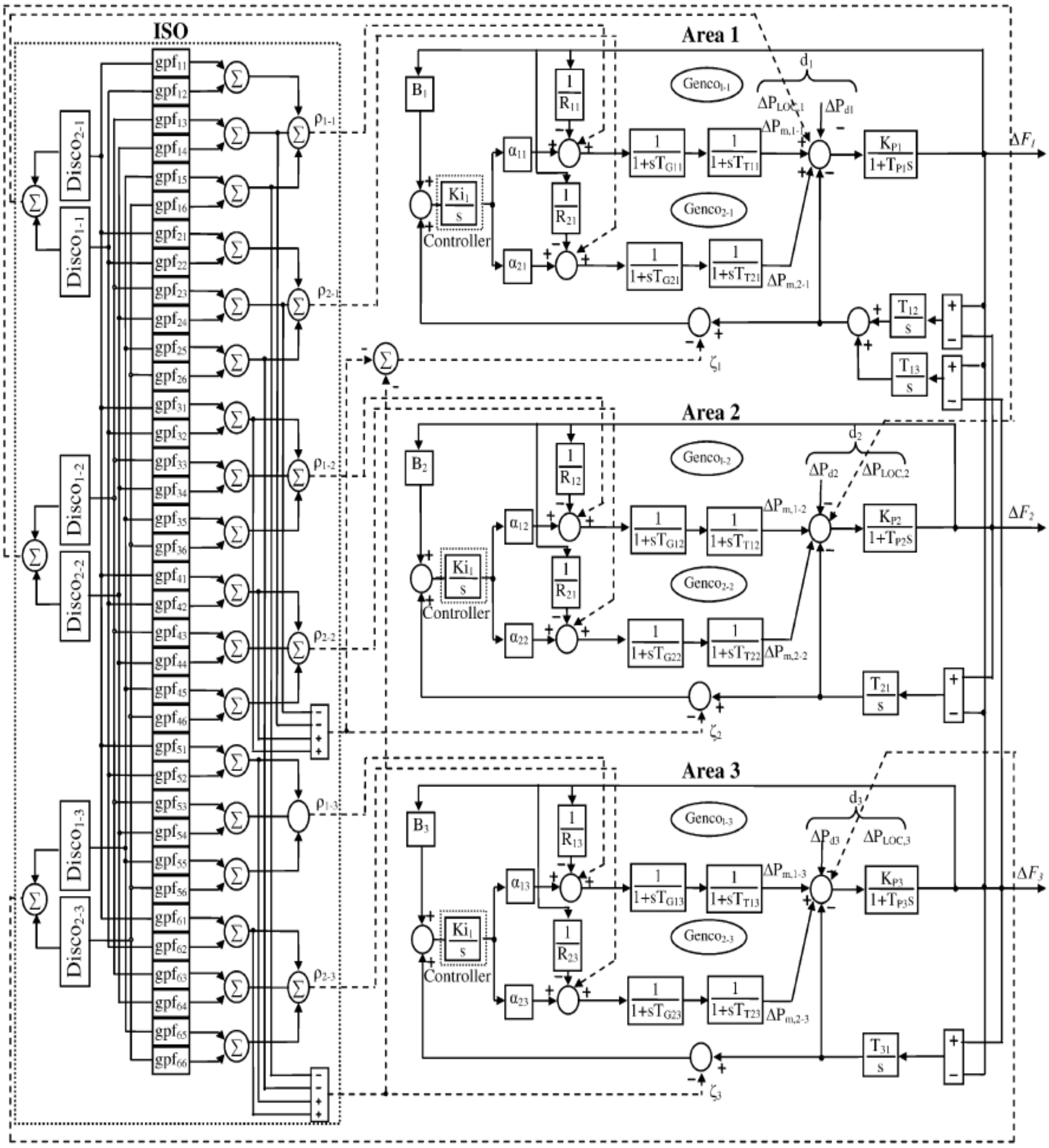



Fig. 1. Adjusted control zone in deregulated environment

## 3. Flower pollination algorithm

Flower pollination algorithm was projected by yang in 2012. FPA is constructed on pollination of flower performance. Abotic or self-pollination and biotic or cross-pollination is the two pollination process of pollination in flowers. In Abotic or local pollination, pollinators are wind and water within a short distance. This pollination is in the similar plant with identical flower or with other flowers. Biotic or cross-pollination or global pollination, pollinators are insects and long-distance plants are considered. The guidelines of natural algorithm are:

1. Cross-pollination process
2. Local pollination process
3. Swapping chance p ∈ [0, 1].

$$vx_i^{a+1} = vx_i^a + S(vx_i^a - b) \tag{3}$$

Where, $vx^a_i$ is the iteration solution, b is the local finest result. S is the power of the fertilization.
The local fertilization and bloom reliability can be signified as

$$vx_i^{a+1} = vx_i^a + \varepsilon\left(vx_j^a - vx_k^a\right) \tag{4}$$

Where, $vx_j^a$ and $vx_k^a$ are pollens of dissimilar blossoms of the same bush. p = 0.8.

### *A. Internal Model Control (IMC) -PID Controller*

It results in a controller with a single tuning parameter
Step 1. The first order model is obtained. Using half rule the delay is modelled.
Step 2. PID-settings solution from a second order model

### *B. FPA Based PID Controller*

**Step1:** Arbitrarily introduces the search operators
**Step2:** Initialize objective function. Alter the situation of inquiry specialists

$$\boldsymbol{k(s)} = \left(\frac{g}{(\tau 1s+1)(\tau 2s+1)}\right)e^{-\theta s} \tag{5}$$

According to the half rule,

$$\tau 1 = \tau x + \left(\frac{\tau y}{2}\right) \tag{6}$$

$$\theta = \theta 1 + \left(\frac{\tau y}{2}\right) + \sum_{j\geq 3} \tau j0 \tag{7}$$

PID-settings result from a second-order model.

$$\tau 1 \leq 8\theta : K = \left(\frac{0.5}{k}\right)\left(\frac{\tau 1+\tau 2}{\theta}\right) \tag{8}$$

$$\tau 2 \geq 8\theta : K = \left(\frac{0.5}{k}\right)\left(\frac{\tau 1}{\theta}\right)\left(1+\frac{\tau 2}{8\theta}\right) \tag{9}$$

**Step 3:** rand < p, overall fertilization occurs else find local pollination

**Step 4:** Assess the new result using the objective function. If new results are improved, update them in the population in the equation 11 and 12.

**Step 5:** Find the current best solution based on the objective fitness value

**Step 6:** Check for maximum generation else go to step 3

## 4. Simulation results

The power of the proposed control method beside convention ranges are accomplished for three circumstances of a possible agreement under various working conditions. In the three-zone arrangement of de regulated environment, every region has two GENCO'S and two DISCO'S in it. The population taken for the simulation in the FPA based PID tuning are 15.The simulation is done using MATLAB programming and maximum of 100 generations has been taken.

### *A. Case 1:POOL CO Based Transactions*

In this situation, GENCO'S take an interest just in load following control of their regions. It is expected that an enormous advance heap of 0.1p.u. is requested by each DISCO'S in area1 and 2. Accept that an instance of pool co-based agreements among DISCO'S and accessible GENCO'S is reproduced dependent on the accompanying AGPM. It is noticed that the zone 3 not in a part of AGC task as shown in table 1.

$$AGPM = \begin{bmatrix} 0.6 & 0.5 & 0 & 0 & 0 & 0 \\ 0.4 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

*B. Case 2: Mixture of POOL CO and Two-sided Transactions*

In this situation, DISCO'S have the opportunity to have an agreement with any GENCO in their two different regions. Consider that the whole DISCO'S agreement with accessible GENCO'S for power according to the accompanying AGPM. All the GENCO'S take part in the AGC task. The GENCO 1 in region 2 and GENCO 2 in region 3 just take an interest for playing out the AGC task in their zones, although additional GENCO'S track the heap interest in their load demand and other Area.

Table 1. Different case with demand signal, tie line power flow deviation and load demand of GENCO

| **Case** | **Demand signal** | **Tie line power flow deviation** |
|---|---|---|
| Pool co based transactions | Δp (area 1 & 2) = 0.2 pu | $\sum_1, \sum_2, \sum_3 = 0$ pu |
| Combination of pool co and bilateral based transactions | Δp (area 1 & 2) = 0.2 pu | case $\sum_2 = 0.025$ pu mw<br>$\sum_3 = -0.025$ pu mw |

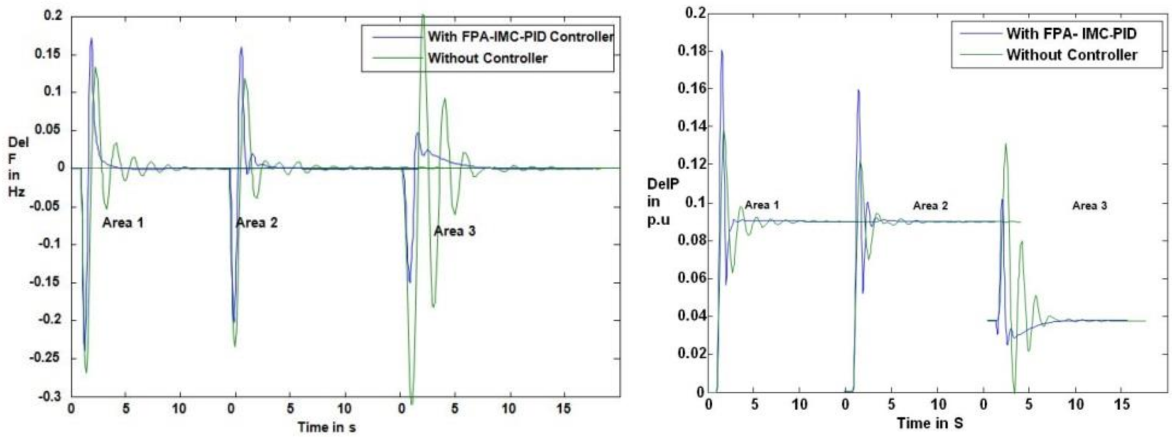
Table 1 presents various scenarios, including those based on Pool Co (collective) and a combination of Pool Co and bilateral approaches. Meanwhile, Table 2 provides information on the demand signal, tie line power flow deviation, and load demand for GENCO. These gains determine the behaviour of the control system in Area 1. A higher proportional gain makes the system more responsive to deviations in frequency, while a higher integral gain helps eliminate steady-state errors. The derivative gain is associated with controlling the rate of change of frequency. These specific values reflect the tuning chosen for Area 1, balancing responsiveness, steady-state accuracy, and damping of oscillations. In Area 2, the gains are slightly different. A higher proportional gain indicates a potentially faster response to frequency deviations, while the integral gain contributes to steady-state accuracy. The derivative gain here appears to be slightly lower, suggesting a slightly less aggressive approach to controlling the rate of frequency change. Area 3 has distinctly different gain values, with a lower proportional gain indicating a less aggressive response to frequency deviations. The integral gain is also notably lower, suggesting a different balance between steady-state accuracy and responsiveness compared to the other areas. The higher derivative gain may imply a focus on controlling the rate of change of frequency in this area.

The choice of these gains reflects the specific requirements and characteristics of each control area within the larger multi-area power system. Tuning control gains is a crucial aspect of AGC to ensure that each area can effectively maintain system stability and respond to disturbances while avoiding excessive oscillations or steady-state errors. The optimal values depend on the dynamics and operating conditions of each area and are determined through extensive analysis and simulations.

Table 2 Determining the Optimal Gain Value for a Three-Area System.

| **Area** | **P** | **I** | **D** |
|---|---|---|---|
| **Area 1** | 1.3976573 | 1.574875 | 0.592669215 |
| **Area 2** | 1.838622189 | 1.780557 | 0.562682155 |
| **Area 3** | 0.706995538 | 0.330612 | 0.715336372 |

The improved PID controllers quickly bring the frequency deviation back to zero and rapidly restore tie-line power deviation to its steady-state value, exhibiting minimal settling time and overshoot. This is illustrated using the figure 2.




(a) (b)

Fig. 2. Del Frequency and Deviations of tie line power flow at area 1,2,3 for case 1 respectively

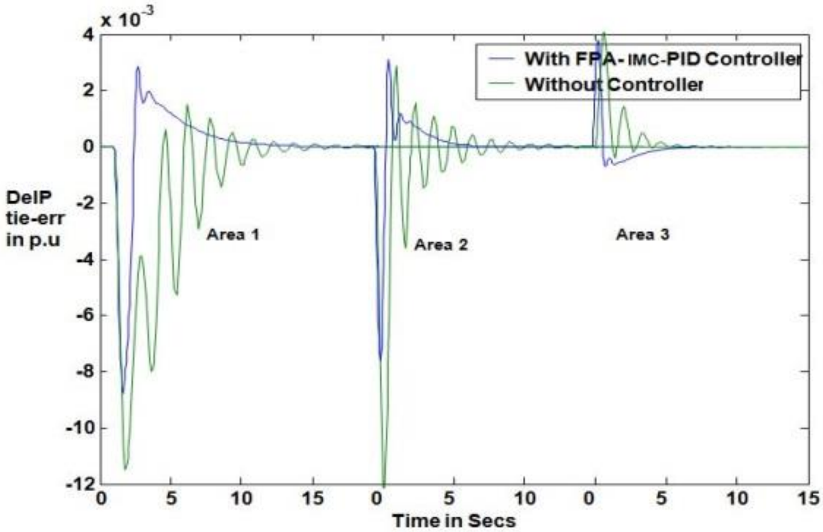



Fig.3. GENCO 1 and 2 power change in area 1,2,3 for case 1 respectively

Due to the absence of agreements between zones, the steady-state power flow through the line remains at zero. Additionally, the real power outputs of the GENCOs are adjusted in accordance with the conditions, effectively converging to the desired value in steady-state conditions with minimal settling time and overshoot. Figure 3 shows the real produced power of the GENCO'S as per condition appropriately merge to the ideal worth in the consistent state with little settling time and overshoot. The estimation of the whole system, conditional upon the number and kinds of generators associated with the system.

Table 3. Optimized PID gain value for three area system

| Area | P | I | D |
|---|---|---|---|
| **Area 1** | 1.023729124 | 0.980476 | 0.573232358 |
| **Area 2** | 1.15122979 | 0.348061 | 0.593943591 |
| **Area 3** | 1.919085624 | 0.896675 | 1.112835992 |

In the case 2, the power produced is converge to the required value while in the stable condition. This is attained with small settling time and overshoot. The values of Δp are 1-1, 2-1, 2-3 = 0.1 pu MW, 1-2, 1-3 = 0.075 pu MW, 2-2 = 0.15 pu MW. Table 3 shows the improved PID acquire an incentive for three area. These improved PID controller acquire esteem immediately determined back the frequency deviation to zero. Furthermore, it is determined back the tie line power deviation to their consistent state esteem with little settling time and overshoot.

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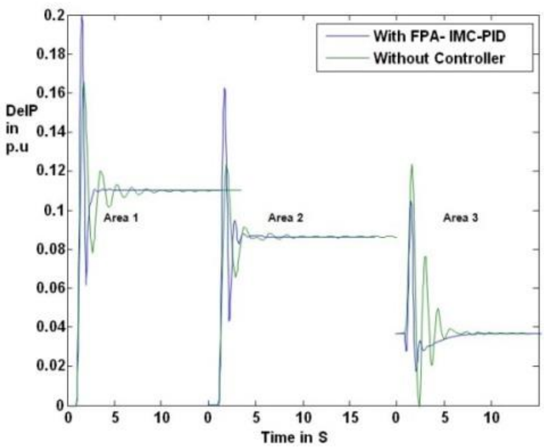
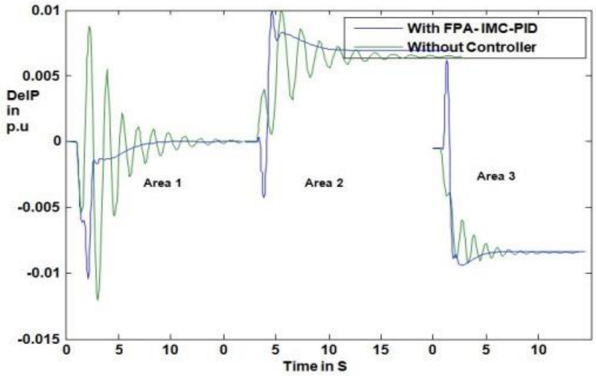
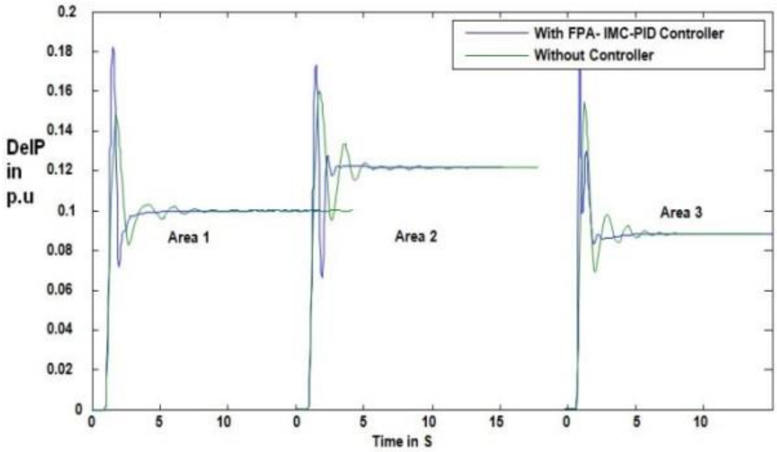
This is illustrated using the figure 4. This is confirmed utilizing the above figure the produced power of the GENCO'S appropriately arrive at their ideal qualities utilizing the proposed technique.




(a)

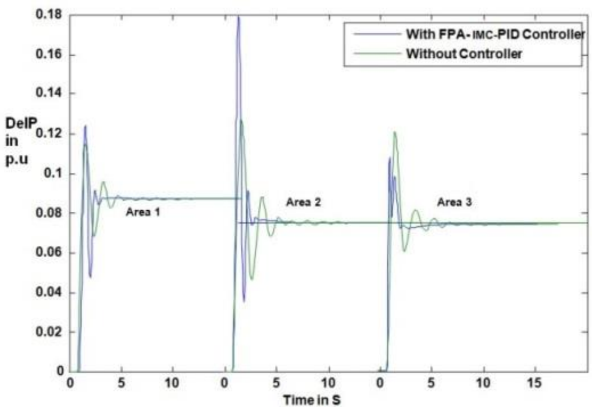



(b)

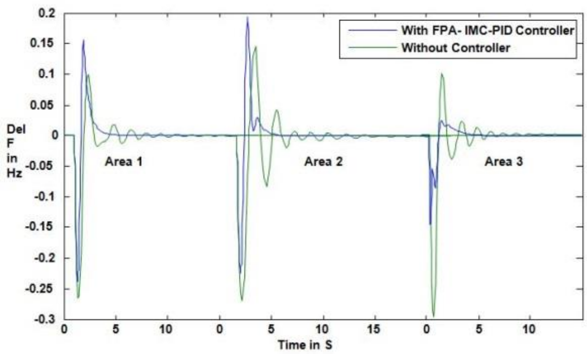



(c)

Fig. 4. Frequency derivations and Deviations of tie line power flow of area 1, 2, 3 for case 2 respectively




(a)




(b)

Fig.5. GENCO 1 and 2 power change in area 1, 2, 3 for case 2 respectively

The simulation results demonstrate that the PID controller based on the Flower Pollination Algorithm (FPA) effectively follows load changes and exhibits excellent stability across a wide range of load disturbances and potential contractual scenarios, even in the presence of nonlinearities within the system. This is visually depicted in Figure 5. Divergences of the frequency and the planned tie-line power flow of the proposed control system. Again the planned controller accomplishes improved restraining for frequency and tie-line power flow deviations altogether three zones. A system ought to consistently be strong enough against boundary varieties of the system. A control system ought to consistently be powerful enough against that the reactions for 20% parameter variety are near the regular case, showing that the proposed controller is very strong.

### 5. Emergency condition

All the induction loads are shut down for (milli seconds to seconds) at 11KV area, there are changes in current, MW and MVA at any emergency condition (blackout). The figure 6 shows the change in current for the area of 1,2,3 due to emergency condition(blackout).Electric power system are among the most mystifying manmade structures on the world. One of the principle issues in power systems is to determine among cheap and safety. The safety of a power system indicates its capacity to give reliable activity regardless of the enormous variety of unsettling influences (varieties in purchaser interest, inside failure, outside irritations like lightning strikes, storms). Security is taken care of by and by through two corresponding procedures : anticipatory control, which is conveyed out by social administrators to keep up the system in a state where it can withstand aggravations; emergency control, which acts naturally after an aggravation has happened in request to limit its results. Meanwhile instabilities are characteristically irregular, preventive control will basically point at adjusting the financial rate of ordinary activity with the danger (anticipated seriousness) of unsteadiness/uncertainty. On the other hand, crisis control basically targets diminishing the seriousness of hazards.

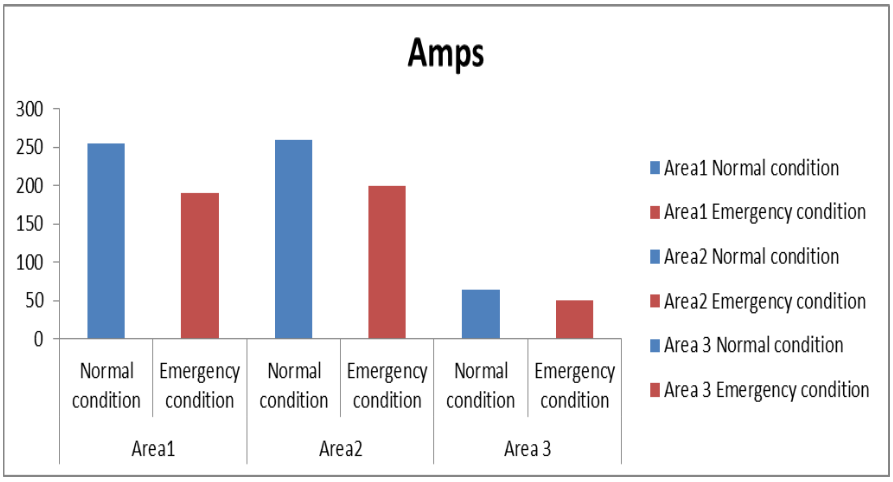



Fig.6. Current change in area 1, 2, 3 due to emergency condition

One of the fundamental issues in the plan of crisis controls is to define suitable measures which can anticipate continuously whether the system is currently loosing firmness or not. This infers the determination of proper real-time estimations (among a large number of potential ones), filtering out the helpful data contained in them, and consolidating these to form location rules. Notice that since crisis controls should work under amazingly severe however rarely noticed conditions, their design method basically depends on mathematical replication of the power system conduct under different conditions prone to drive it towards a uncertainty

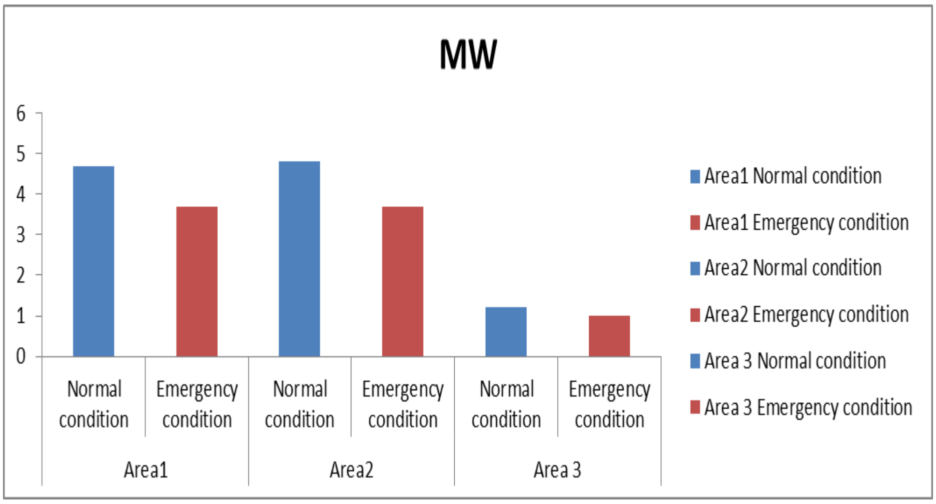


Fig.7. MW change in area 1, 2, 3 due to emergency condition

The figure 6 shows the ampere change in area 1, 2, 3 and figure7 shows the MW change in area 1, 2, 3 due to emergency condition. Mathematical credits are addressed as piecewise straight elements of time, with step sizes differing starting with one item then onto the next and conceivably starting with one quality then onto the next. Note additionally that in our application it is desirable over limit the quantity of various ascribes utilized in a recognition rule, to improve intelligibility to encourage approval of results by human specialists, and furthermore to lessen the expense of real operation. Given the huge size of power systems, the quantity of potential competitor ascribes is anyway enormous.

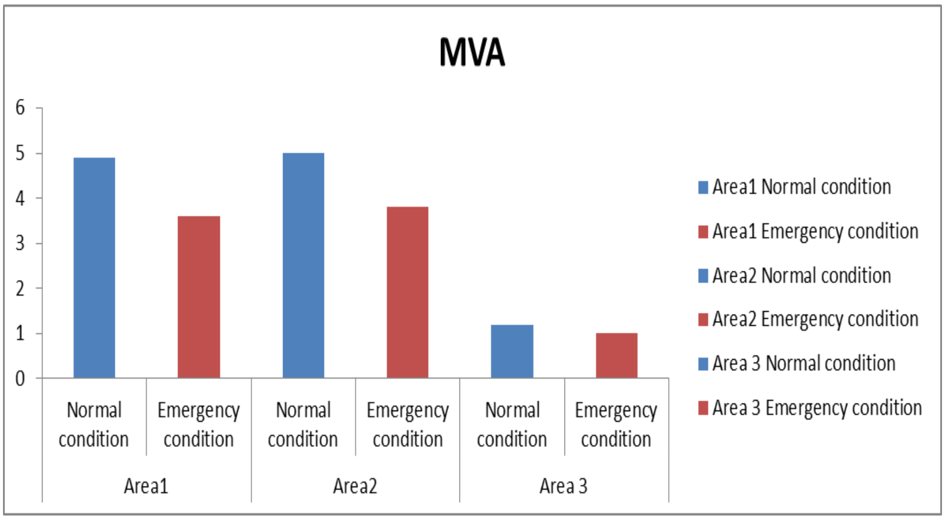


Fig. 8. MVA change in area 1, 2, 3 due to emergency condition

Figure8 shows the MVA change in area 1, 2, 3 due to emergency condition. For instance, we defined the theory space of competitor tests on mathematical ascribes dependent on the way that voltage breakdown might be recognized by noticing monotonically diminishing voltage sizes or potentially excitation flows arriving at their maximum cut-off points. Then again, due to the non-direct conduct of force frameworks it is important to select the fitting areas in the framework where voltages or then again excitation flows ought to be estimated and edges should be adjusted to framework specifics. Operators can utilize this apparatus and feed it immediately also, constantly with the information during the activity of the electric utility to get anticipate for any event of disturbance. The authors accept that expanded comprehension of electrical disturbance can have huge possible advantages to the country power framework activity.

## 6. Discussion

This paper extensively covers the body of literature pertaining to load frequency controller models. It also addresses the most recent challenges and issues faced by these controllers and the power system as a whole in maintaining system frequency within nominal levels while keeping voltage and active power profiles within predetermined bounds. The integration of intermittent energy sources such as solar and wind power, along with energy storage devices, has played a crucial role in enhancing system reliability and the quality of power supplied to consumers. In response, advanced control strategies have been developed over the past few decades to better manage system frequency, which is a critical concern in power system operation and control. As micro grids become more prevalent, especially when connected to the main grid, there is a pressing need to develop frequency control algorithms that can account for their unique dynamics.

Furthermore, the integration of renewable energy sources into the power system adds complexity to the design and operation of frequency regulation. Many existing renewable sources, like wind and solar, have not been actively involved in frequency management, but as their presence grows, it is essential to explore how they can be dynamically integrated into frequency regulation strategies. In practical power system load frequency control, traditional control techniques like PI and PID algorithms are widely used. However, these conventional controllers often fall short when dealing with external disturbances and nonlinearities within the power system. The literature suggests various controller modifications, but many rely heavily on mathematical plant models, making them vulnerable to uncertainties related to load power variations, modelling inaccuracies, and structural changes in the network. The introduction of new control models becomes advantageous in light of these limitations, the increasing integration of renewable energy sources, and ongoing structural transformations in modern power systems.

Comparing the outcomes of the strategies proposed in this research reveals two key advantages. Firstly, the suggested method yields larger stability zones compared to techniques that reduce conservatism in the criteria. Secondly, it effectively highlights interdependencies between different areas within the power system. Traditional load frequency control struggles to uncover such interactions due to obscure coupling connections, while the proposed technique offers more insights into this aspect. The approach for deregulated load frequency control illustrates that as the delay in one control region increases, the delay margin in the other control area diminishes. The proposed stability criterion primarily considers ACE, frequency variations due to disturbances, and the asymptotic stability of load frequency control. However, it does not address specific transient responses of the control system, such as settling time and overshoot of ACE. Complying with control performance standards also requires attention. Additionally, investigating how time delays affect these standards and their relationship, especially in deregulated load frequency control environments, is essential.

## 7. Conclusions

This paper introduces a solution for the AGC (Automatic Generation Control) challenge within a deregulated power system, utilizing an FPA-based IMC-PID controller with a modified AGC scheme. The choice of this control technique is motivated by the increasing complexity and evolving structure of deregulated control systems. This innovative control system combines the advantages of the FPA-based IMC-PID approach with fundamental regulators to achieve optimal performance in terms of reference frequency tracking and disturbance mitigation, especially when dealing with wide-area load variations and conflicts. Moreover, its simplicity in design and implementation makes it highly practical for real-world power systems. To validate its effectiveness, the FPA IMC-PID controller was tested within a three-region deregulated control framework, showcasing its robust performance across various operational scenarios. Simulation results affirm that this proposed approach exhibits exceptional resilience and delivers strong performance even in the face of uncertainties in system parameters and load fluctuations. Consequently, the FPA-PID control scheme emerges as a promising solution for addressing AGC challenges within deregulated power systems. Therefore, it is recommended for the generation of high-quality and reliable electric energy within such deregulated control systems.

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