Optimized Automatic Generation Control of a Two-Area Interconnected Power System Using Artificial Bee Colony Algorithm

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***Abstract*—The frequency of the systems has to be maintained within reasonable ranges to ensure the consistent and proper functioning of the interconnected power systems. The difference in the load demand tends to affect the equilibrium between the power production and consumption causing frequency variation and tie-line power flow variability among connected regions. Automatic Generation Control (AGC) also called Load Frequency Control (LFC) is commonly applied to control the system frequency and keep the planned power swap between control regions. The present paper presents an optimization method using Artificial Bee Colony (ABC) algorithm to tune the parameters of a Proportional-Integral (PI) controller to a two-area interconnected thermal power system. The aim of the suggested approach is to enhance dynamic behavior of the system by reducing frequency variations and tie-line power swings in case of load variations. The controller parameters are optimized with the help of performance index that is dependent on the Integral of Time multiplied Absolute Error (ITAE). The efficiency of the suggested ABC-based controller is tested using simulation works in various load disturbance situations. The findings show that the optimized controller has better damping properties, less oscillations and less time of settling in relation to traditional PI controller tuning strategies. The suggested method provides a straightforward and efficient method of improving the stability and dynamic behaviour of interconnected power systems.**

***Index Terms*—Artificial Bee Colony Optimization (ABC), Automatic Generation Control (AGC), Load Frequency Control (LFC), Two area Interconnected Power System, PI Controller, Power System Stability.**

I. INTRODUCTION

The stability of a power system based on electricity is heavily reliant on the ability to ensure that there is a balance between power generation and the demand of power. In interconnected power systems, even a minor unbalance between generation and consumption can cause deviation in the frequency of the system, and changes in tie-line power exchange between areas of control. The deviation can impact power system stability and achieve poor performance unless the deviations are addressed. Hence, keeping the frequency of systems within reasonable bounds is a critical necessity to secure and reliable operation of power systems.

Generally Automatic Generation Control (AGC), also known as Load Frequency Control (LFC) is commonly used to adjust the frequency of the system and manage the exchange of power among areas connected to each other. AGC has the primary aim of recovering the nominal system frequency and sustaining the planned tie-line peak flow of power after load disturbances. A multi area power system has control areas each charged with the responsibility of adjusting their own generation to frequency deviations and variations of tie-line power.

Conventionally, proportional-integral (PI) controllers have been popularly applied in load frequency control because they have a simple structure and are easy to implement. Nevertheless, sequencing of the conventional PI controllers is very sensitive to the correct tuning of the controller parameters. Poor tuning could result in slow dynamic response, more oscillations, and high settling time when disturbances on the load are introduced into the system. This means that the optimal controller parameter identification has become a significant research issue in the control of power system.

Different optimization methods have been used to tune the AGC parameters in order to enhance the performance of the controllers. Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and other evolutionary optimization methods have been investigated and used to increase the stability of systems and minimize the percentage deviation of frequencies. These methods have performed better than traditional tuning methods but still, there is need to develop efficient optimization algorithms which can give better convergence and better system response.

Several years ago, the use of swarm intelligence-based optimization algorithms has received significant interest in solving intricate engineering problems. The Artificial Bee Colony (ABC) algorithm has become a potent optimization algorithm based on foraging behavior of honey bee colonies and is one of these techniques used. ABC algorithm is highly global search as well as has been effectively applied in other optimization problems because of its simplicity and effectiveness.

This paper is motivated by the benefits of swarm intelligence methods; therefore, it explores the use of Artificial Bee Colony optimization in the process of tuning the parameters of a PI controller in a two-area interconnected power system. The aim is to improve the dynamic performance of the system to minimize the frequency deviations and tie-line power oscillation to various load disturbance conditions. The performance of the given method is tested by the use of simulation studies, and the findings prove the better performance of the optimized controller in system stability.

II. RELATED WORK

Load Frequency Control (LFC) is a significant issue of research in the operation of power systems over decades. The primary goal of LFC is to ensure a constant frequency of the system and adjust the power exchange between connected regions in case of load disturbances. Many control methods and optimization are invented in the past to enhance the performance of Automatic Generation Control (AGC) systems.

Preliminary studies on AGC were mostly based on the classical control methods. The traditional integral and proportional-integral (PI) controllers were considered very popular because of their straightforward design and simplicity in application. These controllers could minimize steady-state frequency error, but usually failed when the system was subjected to sudden load disturbances. Traditional tuning schemes in most instances led to sluggish dynamic response and more extensive oscillations in system frequency.

In order to address such limitations, researchers started using optimization methods to identify the best controller parameters. Tuning AGC controller gains, has extensively been done using Genetic Algorithms (GA) due to their capability of searching optimal solutions in problems which are complex to optimize. The tuning techniques using GA have shown better performance of the system than conventional tuning techniques. Equally, Particle Swarm Optimization (PSO) is also utilized in order to optimize controller parameters of interconnected power systems. PSO is characterized by high convergence and effective search ability that aids in better damping of the system as well as minimizing the deviation in frequencies.

Besides GA and PSO, some other evolutionary optimization methods have been examined into application in AGC. Power systems with multi-areas have been designed with the Imperialist Competitive Algorithm (ICA) to produce powerful controllers that are used in frequency control of loads. Similarly, a Bacterial Foraging Optimization Algorithm (BFOA) has been explored in the optimization of PI and PID controllers to produce better stability and dynamic response in a system within various operating conditions.

In more recent times, attention has been drawn to swarm intelligence-based algorithms because they are useful in managing complex nonlinear optimization problems. The Artificial Bee Colony (ABC) algorithm is one such approach and it is based on the foraging behaviour of honey bee colonies. The ABC algorithm uses the mechanisms of cooperative search of the solution space between the types of bees in the search of optimal solutions. Due to its simplicity and good search capacity globally, the ABC algorithm has been effectively used to solve numerous engineering optimization problems.

This paper is driven by the benefits of swarm intelligence methods and it aims at applying the Artificial Bee Colony algorithm to adjust the settings of a PI controller that is applied in the two-area interconnected power system load frequency adjustment. The objective of the proposed approach is to enhance the dynamic system performance to minimise the frequency deviations and tie-line power oscillations during load disturbance conditions.

III. SYSTEM MODEL OF TWO-AREA INTERCONNECTED POWER SYSTEM

A connected power system is typically separated into several control areas which are linked by transmission tie-lines. Such interconnections allow the interchange of electrical power among various regions and this assists in enhancing reliability and operational efficiency of the systems. But when there is the sudden alteration of the demand in load in one control area then it alters the balance between the generation and consumption of power. This unbalance causes frequency variations in the system and variations in the flow of power across the tie-line between the areas. Thus, a load frequency control (LFC) system is needed to be able to keep the system frequency at its nominal value and provide adequate power sharing among the areas that are interconnected.

A two-zone interconnected thermal power system has been taken into account in this study to study the performance of the proposed control approach. Every control region comprises of a governor, turbine, generator and load model. The governor is the main control component that is able to detect the frequency deviations and modify the input of the turbine. The steam energy is converted to mechanical power by the turbine and then this power is used to run the generator and generate electricity. The generator is used to supply power to the load connected in the control area. A tie-line between the two areas has been established which provides power transfer between the two areas. When there is a load disturbance in a given area e.g., a rise in demand, frequency in the area reduces. Consequently, this causes the supply of more power by the adjacent region via the tie-line to sustain the load. As a result, the disruption influences the two regions of the interdependent system. This is the reason why the two areas should be controlled together in order to restore the system frequency and keep the planned flow of power on the tie-line.

The Area Control Error (ACE) is used to describe the difference between the scheduled and actual values of frequency and tie-line power in multi-area power systems. The signal of the control is ACE, which controls the generation output generated in every area. The system is capable of restoring frequency of the system to its nominal value by adjusting the power generated based on the ACE signal and holding the desired power exchange between the tie-line and the load. To ensure that the analysis is easy, the two control areas in the system are considered to have the same parameters. Two-area interconnected power system model is an appropriate model to be used in investigating the dynamic behaviour of the system when it is perturbed by load disturbances and determining the efficacy of various controller design methods. The model can be extensively applied to the study of load frequency control to study the stability and performance of a system under different operating conditions. Fig. 1 gives the block diagram of the two-area interconnected power system which was used to give the analysis of the AGC.

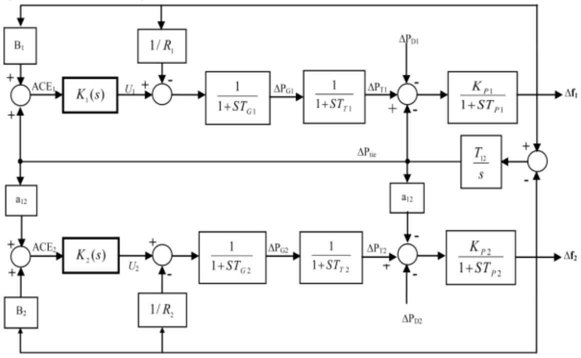

Fig. 1 Two-area interconnected power system model used for AGC analysis.

IV. PROPOSED METHODOLOGY

This paper presents an optimization solution to designing a better performance of Load Frequency Control (LFC) in a two-area connected power system. The suggested methodology is concerned with the fine-tuning of the parameters of a Proportional-Integral (PI) controller with the help of the Artificial Bee Colony (ABC) optimization algorithm. This is the primary goal to reduce frequency variance and tie-line power swings that arise as a result of load disturbances in the interconnected system. The general scheme of the suggested control method is shown in Fig. 2.

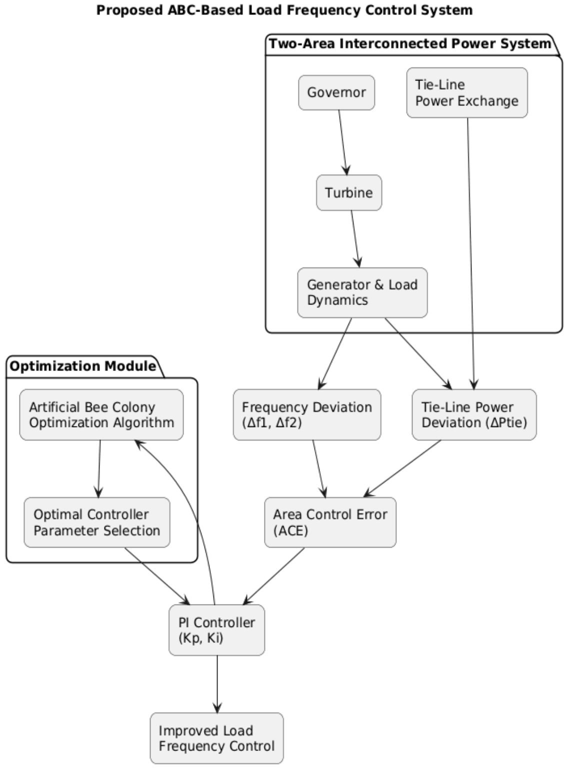

Fig. 2. Proposed Artificial Bee Colony based load frequency control framework for a two-area interconnected power system.

PI controllers are usually employed in traditional load frequency regulation due to their straightforward design as well as their successful performance in minimizing steady-state errors. The effectiveness of a PI controller is however to a large extent determined by the adequate choice of proportional and integral gain parameters. Poorly adjusted parameters can cause poor system response, large oscillations and longer settling time. As such, it is critical to decide the best controller parameters to enhance the performance of the power system.

Within the given approach, optimization is applied to the tuning of PI controller parameters. To find the best possible values of the controller gains with the best system performance; the Artificial Bee Colony algorithm is used to search. The ABC algorithm relies on the foraging behavior of honey bee colonies and can efficiently search the search space in order to find the best solutions.

Initialization The optimization process starts with the initialization of a space of potential solutions which are combinations of various controller parameters. The solutions are ranked by their performance index which is an indicator of system response quality during load disturbances. These solutions are then improved systematically by the cooperative efforts of the employed bees, onlooker bees and scout bees. Existing solutions are explored by employed bees; promising solutions are chosen based upon their quality by onlooker bees as well as random searches of new solutions are made when existing solutions do not improve anymore.

As illustrated in Fig. 2, the two-area interconnected power system produces frequency variations and tie-line power variations in case of load disturbances. These deviations have been utilized to calculate the Area Control Error (ACE) which is fed to the PI controller. The Artificial Bee Colony optimization algorithm keeps on varying the parameters of the controller to achieve the best performance.

ABC algorithm can find the optimum controller parameters that ensures the minimization of the performance index and maximization of system stability through this iterative search process. The optimized PI controller is then implemented to the two-area interconnected power system to control the frequency deviations and tie-line power fluctuations.

Its general methodology is the two-area power system modeling, PI controller design, Artificial Bee Colony algorithm to optimize the parameters and finally assessing the system performance by using the simulation studies. The proposed solution is expected to bring an increase in the quality of dynamic response and frequency regulation in interconnected power systems by combining swarm intelligence as an optimization tool with traditional control methods.

V. ARTIFICIAL BEE COLONY OPTIMIZATION

Artificial Bee Colony (ABC) optimization is a metaheuristic algorithm optimization involving a population that relies upon foraging ants of honey bee colonies. The algorithm was proposed to address the difficult optimization problems and it was based on simulating the intelligent food seeking behavior of the bees. Over the past few years, the use of ABC optimization has received a lot of attention in engineers due to their simplicity, flexibility, and the capacity to search the search space easily to get the best solutions.

In this study, the Artificial Bee Colony algorithm will be utilized to calculate the optimum parameters of the PI controller that will be applied in load frequency control of a two-area interconnected power system. The algorithm is used to seek the controller gain values which maximize the performance index and enhance the dynamic performance of the system.

A. Overview of ABC Algorithm

Artificial Bee Colony algorithm relies on the collective behaviour of honey bee colonies in search of sources of food. In a normal colony of bees, bees collaborate with one another in order to find food sources containing the best nectar quality. ABC algorithm models this cooperative behavior in solving optimization problems.

In the algorithm, each possible food solution to the optimization problem is a food source. The fitness of a solution is related to the source of food quality. In the algorithm, a starting population of solutions, which are randomly chosen in the search space, is used. The solutions are then enhanced with time as artificial bees visit and exploit search space to get improved solutions. The primary task of the algorithm is to find the food source containing the largest amount of nectar, which represents a solution of the optimization problem of the greatest value.

B. Working Principle of ABC Algorithm

The ABC algorithm working process comprises the task of initializing a number of food sources that can identify a possible solution to the optimization problem. The employed bees apply changes to the existing solution to produce a new candidate solution. The equation below is used to generate the new solution:

$$V_{ij} = X_{ij} + \phi_{ij}(X_{ij} - X_{kj})$$

where

- X_{ij}represents the current solution
- $X_{kj}$is a randomly selected neighbor solution
- $\phi_{ij}$is a random number within the range $[-1,1]$

In case the new solution created is more fit than the old solution, the new solution takes its place.

Onlooker bees choose the sources of foods according to the probability value calculated by the fitness of solutions. The probability of selection is as follows.

$$P_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n}$$

where

- fit_irepresents the fitness value of the solution
- SNrepresents the total number of food sources.

C. Mathematical Representation of ABC

In case the solution cannot improve over a predetermined number of iterations, it is said to be abandoned. The bee that has been deployed in this instance becomes a scout bee and creates a new solution randomly with the help of.

$$X_i = X_{min} + rand(X_{max} - X_{min})$$

where

- $X_{min}$and X_{max}represent the lower and upper bounds of the search space
- $rand$is a random number between 0 and 1.

The Artificial Bee Colony algorithm is able to find an optimal solution through trial and error, which involves exploration and exploitation of the search space. In this study, the algorithm is used to identify the ideal parameters of the PI controller to enhance the load frequency control of the interconnected power system of the two areas.

VI. PI CONTROLLER DESIGN

In interconnected power systems, the frequency of the system should be kept within acceptable limits in order to have stable and reliable operation. When there are load imbalances in one control area, frequency errors and tie-line power variation may occur between the areas that are interconnected. Controllers are employed to control such deviations and bring the system back to its nominal operating condition, which is a part of the Automatic Generation Control (AGC) mechanism.

The Proportional-Integral (PI) controller is one of the commonly used controllers which have a simple structure but good control performance and are mostly applied in load frequency control applications.

The PI controller is based on the proportional plus the integrational actions of control to minimize the steady-state error and enhance the dynamic response of the system. The proportional element reacts to the present worth of the error signal, whereas the integral element eradicates the steady-state error by integrating the error with time. General transfer action of PI controller may be given as.

$$K(s) = K_P + \frac{K_I}{s}$$

Where

$K_P$represents the proportional gain and $K_I$represents the integral gain of the controller. These parameters determine the effectiveness of the controller in regulating system frequency and tie-line power deviations.

In a two-area interconnected power system, PI controller is used in each control area to process the Area Control Error (ACE). ACE signal is the difference between the scheduled and actual values of frequency and tie-line power. The PI controller output is utilized to modulate the reference power input to the governor that in turn controls the turbine and generator output to recover the system frequency.

The gain parameters of a PI controller are more or less a determining element of its performance. Badly adjusted controller gains can cause dynamic behavior that is bad, e.g., large oscillation, long settling time and poor damping of frequency variations. Consequently, it is a significant undertaking to define the best values of the controller parameters in load frequency control design.

In this paper, the Artificial Bee Colony optimization algorithm is used to optimize the parameters of PI controller. The optimization process is aimed at finding the most appropriate values of proportional and integral gains that achieve the performance index minimum and the overall system dynamic response maximum. It is expected that with the proposed approach, the two-area interconnected power system can be better regulated in terms of frequency regulation and stability by adjusting the parameters of the controller with the help of the ABC algorithm.

VII. OBJECTIVE FUNCTION

The choice of the right objective function is significant in the development of a controller via optimization so that the desired system performance is attained. The objective function is applied to determine the quality of the system response and direct the optimization algorithm to the optimal controller parameters. The objective function proposed is to reduce the frequency deviations and tie-line power variation which happens as a result of load disturbance in the interconnected power system.

To solve issues of load frequency control, Integral Square Error (ISE), Integral Absolute Error (IAE), and Integral Time multiplied Absolute Error (ITAE) are different performance indices that are usually employed to measure system performance. Of these indices, the ITAE criterion is the most popular as it is effective in penalizing large errors that last longer and assists in attaining quicker settling time with less oscillations.

In this paper, Integral Time multiplied Absolute Error (ITAE) is the performance index that is taken to optimize the PI controller parameters. The goal of the optimization process is to achieve a maximum reduction in the ITAE value of the frequency deviations of both areas, as well as, the tie-line power deviation. The objective function may be denoted as.

$$J = \int_0^T t\,(\mid \Delta f_1 \mid + \mid \Delta f_2 \mid + \mid \Delta P_{tie} \mid)dt$$

where

$\Delta f_1$and Δf_2represent the frequency deviations of Area 1 and Area 2 respectively, and ΔP_{tie}represents the tie-line power deviation between the two areas. The variable Tdenotes the total simulation time.

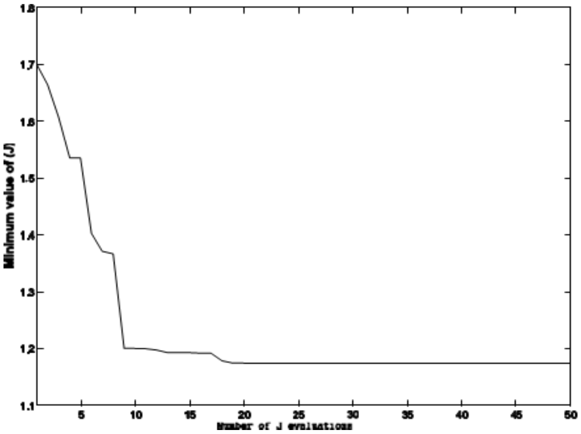

Fig. 3 Progress of the objective function during ABC optimization.

The optimization algorithm can find the optimal values of the PI controller parameters that can minimize frequency oscillations and increase the dynamic performance of the system by minimizing the value of the objective function J. The optimization process assists in attaining improved damping properties, reduced settling time as well as enhanced stability of the linked power network during various load disturbance circumstances.

VIII. SIMULATION RESULTS AND DISCUSSION

In order to assess the performance of the control strategy proposed, simulation studies were conducted on a two-area interconnected thermal power system. The simulations were done to examine the dynamic response of the system with varying load disturbance conditions. The operation of the frequency deviation and tie-line power variation of the Artificial Bee Colony (ABC) optimized PI controller was analyzed. The findings in the simulations depict that the proposed controller can enhance the stability of the system and decrease oscillations in the interconnected power system.

A. Load Disturbance in Area 1

In test case one, an incremental load demand is caused to Area 1 of the interconnected power system whilst Area 2 was held constant. This unsteady condition leads to the short-term generation-load imbalance in Area 1, causing the system frequency deviation and change in the power flow in the tie-line between the two areas.

The outcomes of the simulation indicate that the frequency deviation in the first area (Area 1) immediately increases because of the abrupt load change. As the application of the optimized PI controller is done, however, the system stabilizes sufficiently and the frequency recovers its nominal value. The tie-line power also modifies it in line with the load demand that is high. The controller is effective to reduce oscillations and shortens the settling time, which proves to be better in response to a load disturbance condition on the system.

Figs. 4-6 show the frequency deviations of the two areas, and tie-line power response of a load disturbance of 0.1 p.u load disturbance on Area 1.

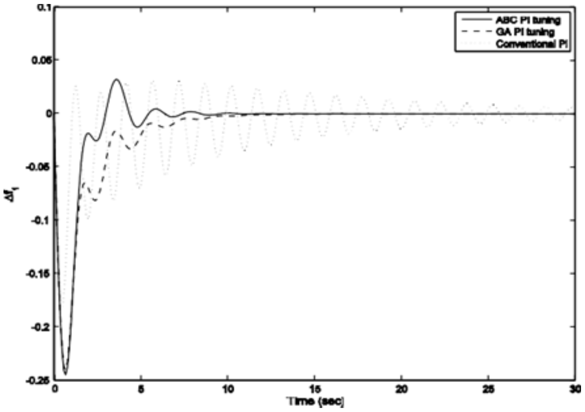

Fig. 4 Change in f1 for 0.1 p.u step increment in PD1.

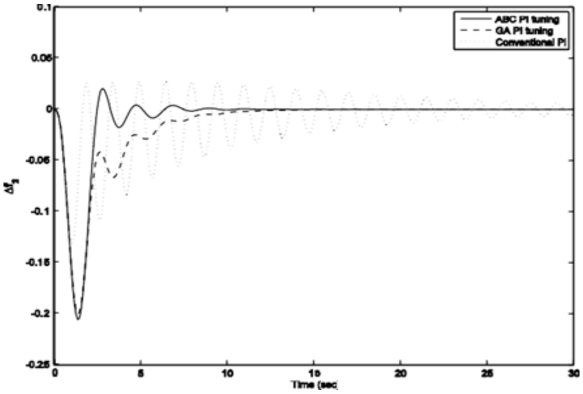

Fig. 5 Change in f2 for 0.1 p.u step increment in PD1.

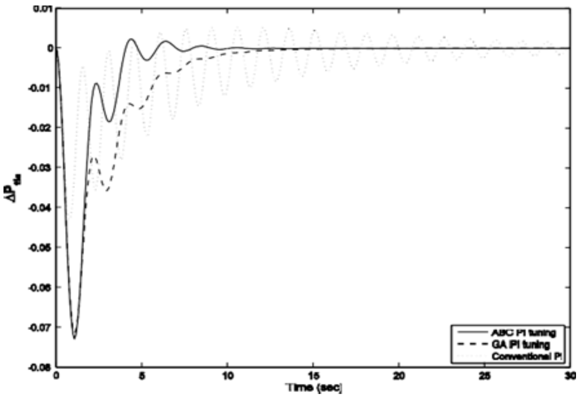

Fig. 6 Change in Ptie for 0.1 p.u step increment in PD1.

B. Load Disturbance in Area 2

The second test scenario is in which a step load disturbance is applied in Area 2 with Area 1 under normal conditions. In the same manner as in the earlier example, the disruption results in variations in the frequency of the system, and a shift in the power flow between the two areas of control in the tie-line.

According to the simulation findings, the proposed controller is efficient to control the frequency deviations in both locations. The nature of the system chain is such that the frequency response of Area 1 is also disturbed by the perturbation in Area 2. The PI controller is however optimized and in a short period of time, it is able to counter the disturbance, and returns the system to its steady-state. The findings show that the proposed control mechanism is stable in the behavior of the system whenever disturbances are introduced in other fields. Figs. 7-9 give the dynamic responses of the system to a 0.1 p.u load disturbance at Area 2.

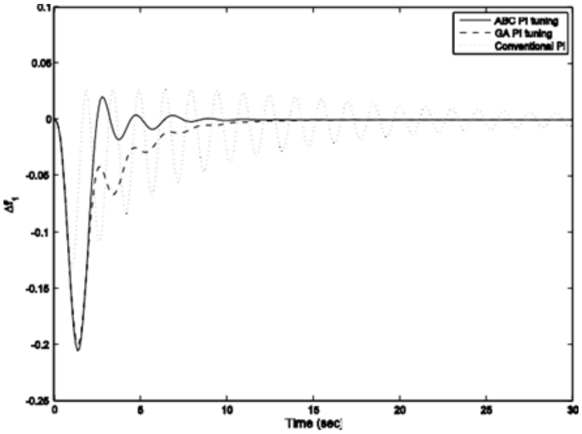

Fig. 7 Change in f1 for 0.1 p.u step increment in PD2.

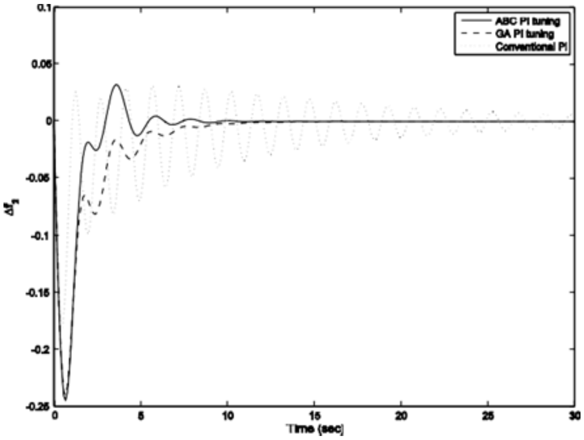

Fig. 8 Change in f2 for 0.1 p.u step increment in PD2.

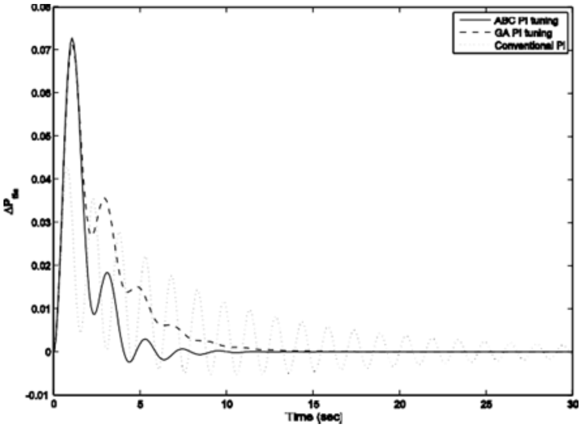

Fig. 9 Change in Ptie for 0.1 p.u step increment in PD2.

C. Simultaneous Load Disturbance in Both Areas

In the third case, step load disturbance is introduced to both control areas of the interconnected system simultaneously. This situation is a more difficult operating case where both locations have a change in the load simultaneously.

As indicated in the results of the simulation, the system at first undergoes greater frequency deviations because of a combination of the disturbances. In spite of this situation, the optimized PI controller is able to stabilize the system and reduce oscillations in a short time. The controller is effective in coordinating the generation of power of both areas to restore the system frequency and sustain the planned tie-line power exchange. This shows how strong the proposed control strategy is in various cases of disturbances.

The response of the system to concurrent load perturbations in the two control regions is shown in Fig. 10.

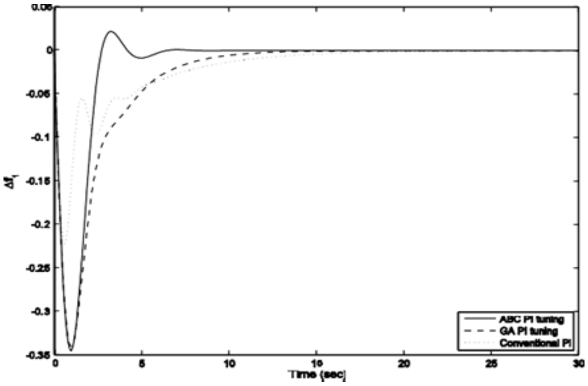

Fig. 10 Change in f1 for 0.1 p.u step increment in PD1 and PD2.

D. Parameter Variation Analysis

In order to test the strength of the proposed controller further, the parameter variation test is conducted by changing some of the system parameters in a given range. This test is applied to investigate the controller behavior in uncertain conditions of the system.

The findings show that a controller that has been optimized ensures a stable system performance with varying system parameters. The deviation in frequency and variation in tie-line power levels are within acceptable levels and the system adapts very easily back to the steady-state. This identifies the fact that the proposed PI controller based on the ABC offers sound performance and better stability in the event that the parameters uncertainties occur.

In order to test the strength of the controller, the tie-line synchronizing coefficient T12 is adjusted by +-50% and the system response is presented in Fig. 11.

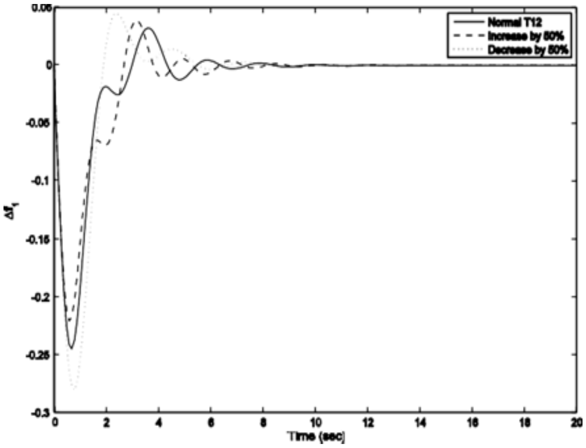

Fig. 11 Change in f1 due to ±50% perturbation in T12.

IX. PERFORMANCE COMPARISON

The proposed optimization approach is tested with respect to the performance of Artificial Bee Colony (ABC) optimized PI controller and the conventional PI controller, as well as other popular optimization-based tuning methods. This is done by comparing the key performance variables like settling time, oscillation damping, frequency deviation and tie-line power variation in case of load disturbances.

In the traditional method, the PI controller settings are usually determined either by hand tuning or by classical tuning. These methods have the capability of reducing steady-state error, but tend to make the system slow to respond to, and larger oscillations occur when the system faces abrupt load disturbances. Consequently, the dynamic system performance might be unsatisfactory in different operating conditions.

Conversely, the optimization techniques focus on identifying the best controller parameters that give better performance of the system. This paper applies the Artificial Bee Colony optimization algorithm to optimize the proportional and the integral gain of the PI controller. The algorithm optimizes the set of parameters that reduces the performance index in the case of frequency deviation and tie-line power variation.

The finding of the simulation proves that the PI controller optimized by ABC shows quite a lot of improvement in the performances of the systems in comparison to the conventional PI controller. The controlled controller is smoother in its settling time and less overshoot with a better damping property. The frequency variations in both the control areas are brought to a minimum and the tie-line power oscillations are much lesser.

In addition, the controller based on the ABC system can be characterized as stable in the case of various loads disturbance and parameters change. It means that the optimization algorithm can be used to find the controller parameters that can improve the dynamic response and the robustness of the system.

In general, the comparison of the performances establishes that the Artificial Bee Colony optimization method is a truer solution to the optimization of PI controller parameters to be utilized in load frequency control processes. This suggested solution enhances stability in a system and quicker restoration of system frequency after load perturbation in interconnected power systems.

Table I is a summary of the eigenvalues, minimum damping ratio, controller parameters, values of the objective functions, and settling time calculated with Conventional PI, GA-PI, and ABC-PI controllers.

Table I - System Eigenvalues, Minimum Damping Ratio, Controller Parameters, Objective Function (J), and Settling Time (Ts)

	Conventional PI	*GA-PI*	*ABC-PI*
Eigenvalues	-13.7342	-13.1203	-13.0672 -13.0349 -0.5348 ±j3.0029 -0.8759 ±j1.6251 -0.8733 ±j0.5149 -1.0965
	-13.6218	-13.1043	
	-0.086 ±j4.1699	-0.5605 ±j3.1716	
	-0.9568 ±j3.402	-1.1751 ±j1.9112	
	-1.8538	-1.1967	
	-0.2359	-0.4454	
	-0.2355	-0.4288	
□*min*	0.021	0.17	0.17
K_p,	K_p=-0.7005,	K_p=-0.2346,	K_p=-0.3118,
K_I	K_I=0.3802	K_I=0.2662	K_I=0.4585
J	3.5795	2.554	1.164
T_S	29.42 *sec*	8.56 *sec*	5.255 *sec*

X. CONCLUSION

The paper introduced a method of optimization in enhancing performance of Automatic Generation Control in a two-area interconnected power system. The experiment aimed at the use of Artificial Bee Colony optimization algorithm to tune the parameters of Proportional-Integral controller in load frequency control. The aim of the suggested approach was to minimize fluctuations in frequency and fluctuations in tie-line power that are caused by load anomalies in interconnected power systems.

The model was a two-area thermal power system that was considered to test the performance of the proposed control strategy. The Artificial Bee Colony algorithm was used in order to optimize the PI controller parameters to achieve a better dynamic response of the system. Simulation studies were used to determine the effectiveness of the proposed approach in various operating conditions, such as, load perturbations in a single area, load perturbations in both areas, and perturbations in the system parameters.

The outcomes of the simulation showed that the optimized controller has a substantial positive impact on the stability and dynamic performance of the system. The suggested controller is effective in the reduction of oscillation, minimization of frequency variations, and the attainment of shorter settling time than the conventional PI controller tuning techniques. Moreover, the controller ensures a steady performance of the system despite the variation in system parameters, which suggests its stability in case of unpredictable working conditions.

The obtained results on the whole support the hypothesis that the Artificial Bee Colony optimization algorithm is a useful method of optimizing the parameters of PI controllers in load frequency control problems. The suggested solution offers a better stability of the system and performance of interrelated power systems.

XI. FUTURE WORK

Even though the proposed Artificial Bee Colony optimized PI controller has shown better results in controlling the frequency deviation and tie-line power variation in a two-area interconnected power system, additional research can be conducted to improve the effectiveness and applicability of the proposed concept.

The research area in future work can be to expand on the proposed control strategy to multi-area interconnected power systems that encompass areas other than two. Actual power systems are typically made up of a number of interconnected regions, and experimental analysis of the performance of the controller in these complex configurations would give a better understanding of how practicable the controller can be. Moreover, the proposed approach can be experimented with the power plants of various kinds, including hydro, gas, and renewable-powered generation systems, to study how it can be flexible under various operating conditions.

The possibility to use hybrid optimization methods integrating the Artificial Bee Colony optimization with other smart algorithms has also become another possible path of future research in order to enhance the convergence speed and optimization accuracy. The combination of the state-of-the-art control techniques, including, but not limited to, fuzzy logic controllers, adaptive controllers, or model predictive control with the ABC optimization strategy might also benefit the performance of the system.

Moreover, the practical constraints like generation rate limitations, communication delays and non-linear features of the system can be included in future studies in order to create a more realistic model of an interconnected power system. The applicability of the proposed controller would also be confirmed by implementing the proposed controller in a real-time simulation environment or in hardware-based platforms.

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