Improved Frequency Regulation in Microgrids using Metaheuristic Algorithms

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ABSTRACT:
This research article describes the frequency regulation of an interconnected power system that includes wind energy systems and thermal non-reheat systems, with a Proportional Integral Derivative (PID) controller optimized using metaheuristic algorithms such as Genetic-Algorithm (GA), Harmony-Search-Algorithm (HSA), Bat-Algorithm (BA), and Flower-Pollination-Algorithm (FPA). With the demand for precisely efficient energy systems growing, system engineers are increasingly looking for the finely optimized control solution that also has the benefit of faster convergence and avoids entrapment in local minimal. To minimize the fitness function which is based on ITAE (Integral of Time multiplied Absolute Error) criteria composed of frequency and tie-line power changes, we have obtained an optimum solution in terms of PID controller gain values using the metaheuristics optimizing techniques. Change in frequency in area 1, deviation in tie-line power, and change in frequency in area 2 obtained from different techniques are compared. The results obtained by simulating MATLAB/Simulink convey that PID controller gain values optimized using the HSA technique provide better dynamic performance compared to BA, FPA and GA techniques. The simulation results have been experimentally validated using hardware-in-loop (HIL) on a real-time simulator based on field-programmable gate arrays (FPGA). The HSA optimized PID controller is used to investigate the robustness of the system by Step-Load-Perturbation (SLP) and Random Step Load Pattern (RSLP). Results obtained by running simulation also show that the HSA optimized PID controller for the same optimized gain value can withstand the SLP and RSLP variation made in the system.

KEYWORDS: Bat-Algorithm (BA); Load-Frequency-Control (LFC); Flower-Pollination-Algorithm (FPA); Harmony-Search-Algorithm (HSA); Proportional-Integral-Derivative (PID); Hardware in Loop (HIL).

1. INTRODUCTION

A complex system with numerous interrelated active components makes up the power system. Engineers have had a difficult time keeping up with the ever-changing demands of consumers. The provision of appropriate generation, transmission, and distribution of electric energy is the priority of the power system businesses. The requirement for energy has grown critical for households and industries as a result of tremendous technological advancements [1]. Although they comprise diverse sources like fossil fuels, biomass, wind, solar thermal energy, etc, power networks are getting increasingly complex. Renewable energy sources have made a substantial contribution to the energy supply for power grid sectors. However, due to the constant fluctuation in load, maintaining steady and high-quality energy output in the power system remains a considerable difficulty. To provide optimum energy distribution to consumers, the active power generated must be equal to the energy demand; otherwise, the generating unit's frequency will be significantly impacted. The generator unit's frequency and speed start to decline as the amount of electricity produced drops below the necessary level. Over time, the difference between the energy generated and the needed load demand causes the voltage profile and nominal frequency of the system to change [2][3]. To counteract the effects of variations in the frequency of the system and loading on the tie-line, the Automatic Generation Control (AGC) control method is used to maintain the frequency and provide load interchange with other areas, as well as to regulate each generation unit's active power

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output and deviation in the active power within the control zone. As a result, maintaining a controllable level of tie-line power and frequency for the system is the main objective of AGC. Several approaches to accomplish this have been researched in the past, incorporating but not restricted to adaptive control [4], classical control [5], robust control [6], optimal control [7] and artificial neural network [8]. To attain acceptable frequency and tie-line power stability, many newly developed power systems demand an efficient controller and more inventive optimization methodologies [9]. Over the years, the PID controller has been used in a variety of industrial applications. This is due to its simple compositional structure, exceptional capabilities, and numerous other benefits [10][11][12].

To analyze the dynamic performance of the system under numerous system disruptions, many control approaches in the area of LFC in an interconnected power system that incorporates wind energy systems have been reported in the literature to date. As a result, these solutions range from conventional droop controllers to sophisticated control schemes that aid in AGC in both traditional and distributed power generation systems [13]. As a result, the use of such control techniques in microgrids analyses many elements of secondary load frequency regulation [14]. A fuzzy-based PID controller was designed in [15] to regulate the power fluctuation in the microgrid by coordinating the fuel cell and aqua electrolyzer. Furthermore, advanced control methods based on modern LFC techniques, including sliding mode control [16], neural network control [17] and internal mode control [18], have been given more consideration recently. Regarding the LFC issue in interconnected power systems, there are numerous evolutionary algorithm-based PID and PI control methods. To mention a few previous works, the firefly algorithm [19], differential evolution [20], the genetic algorithm [21], multi-objective optimization using weighted sum artificial bee colony algorithm [22] and the hybrid-particle swarm optimization [23] are some of the examples using an evolutionary algorithm for the tuning of PID and PI controllers gain values for the LFC problem. Furthermore, physical restrictions like generation rate constraint (GRC) for steam turbines, time delay (TD) at unit control outputs, and the dead band (DB) for governors were not taken into account in recent research [24]. In [25], author has discussed robust frequency control strategies that take into account the microgrid system's uncertainties to improve both the microgrid system's nominal performance and robustness. However, one of the disadvantages of robust frequency regulation is the requirement for a priori specified uncertainty limits. Furthermore, asymptotic stability of robust control tracking error performance is difficult to achieve. However, further improving the LFC dynamic performance of an interconnected power system with distributed generation, particularly in the context of given physical limits and dynamic load changes, is a major challenge [26][27].

Depending on how the algorithms were configured, the researchers classified optimization algorithms into two classes: stochastic algorithms, which frequently produce different results each time using the same initial values, and deterministic algorithms, which lead to the same results when using constant primitive values at the beginning of repetition. Heuristic and meta-heuristic algorithms are subclasses of the second class as well. A metaheuristic algorithm is a sophisticated search technique that directs search agents to the most practical area of the search space. The genetic algorithm, the evolutionary algorithm, and swarm intelligence-inspired algorithms are examples of metaheuristic algorithms. Through a careful balance of exploration and random search, these algorithms have recently demonstrated their effectiveness in tackling optimization problems, particularly non-linear ones. Meta-heuristic algorithms were frequently employed to find as good of a solution as an optimal one in an acceptable amount of time and money. The effectiveness of meta-heuristic algorithms and their use in numerous real-world issues are attributed to a variety of aspects, including their simplicity and ease of implementation and their capacity to resist becoming trapped in the local optimal solution [28].

Early in the 1960s and 1970s of the previous centuries, at Michigan University, researcher John Holland created the Genetic Algorithm (GA) in collaboration with a group of his colleagues and students. This marked the beginning of the evolution of nature-inspired algorithms. This algorithm's primary goal was to research natural adaption phenomena and attempt to replicate them in digital systems [28]. Harmony search (HS), which imitates the act of musical improvisation, is a relatively recent evolutionary search-based optimization technique that is quickly gaining popularity [29][30]. Due to its advantages of a simple concept, simple operation, and great efficiency, it has received a lot of attention since its creation. Similar to how artists look for the pleasing harmony specified by an aesthetic standard, the HS principle involves aiming to identify the global optimum under the analysis of an objective function [31]. Bat algorithm is a newly developed, nature-inspired metaheuristic algorithm for various optimization problems. This approach is based on how microbats use echolocation. These creatures have developed echolocation as a hunting tool, and they also have a remarkable guiding mechanism that allows them to discriminate between prey and other obstructions even in a dark environment [32][33]. Another newly developed metaheuristic algorithm is the Flower Pollination Algorithm (FPA) to resolve the optimization issues and this method mimics the flower pollination process. To create a balance between explorative and exploitative ranges mode, FPA has the unique advantage of being able to use both long-distance pollinators and floral consistency (both local and global search) [34]. The combination between these ranges and the algorithm's wonderful convergence characteristics both help to increase its effectiveness. FPA's special local/global search characteristics have made it possible for it to seamlessly adapt to a variety of sectors and offer ideal solutions with little downsides (while keeping an impressive convergence rate) [35][36].

The above-mentioned analysis suggested that there is a need for verifying dynamic performance characteristics for LFC of two area power system integrated with the wind energy system in real-time. In this proposal, the controller used is PID and for its gain values, different optimization techniques were used such as GA [21], BA [33], FPA [34] and HSA [29]. As the objective function based on ITAE criteria has been used by many researchers [7], [37] and [38] due to its significant features, especially for the dynamics performance, therefore, this performance criterion is considered for the optimization of derivative, integral and proportional gain values of PID controller and HIL on an FPGA based OPAL-RT (OP5700) used as a real-time simulator.

This article's remaining sections are organized as follows. The dynamic system modeling of the proposed two-area power system integrated with wind energy is presented in Section II. The objective function design and control signal is outlined in Section III. The different optimization techniques for PID controller gain values are introduced in Section IV. The simulations of various comparative studies on LFC in MATLAB/SIMULINK and OPAL-RT (OP5700) in the event of load disturbances and discussions on the results obtained are represented in Section V. The conclusion of this article is mentioned in Section VI.

2. DYNAMIC TWO-AREA POWER SYSTEM MODELING

In an interconnected power system, the load changes very frequently, as a result, there is a deviation in the frequency and tie-line power. Thus, distributed energy generators are needed to generate less or more electrical energy to cope with the demanded load for the maintenance of energy balance in the tie lines which connects the different areas. When there is less generation as compared to the applied load, then the speed of the generator and thus the frequency will drop, therefore scheduled power levels in the system show changes. Fig. 1 below shows the block diagram of the turbine along with its governor. The operating limit of the tie-line and the generator is not allowed to exceed and it is ensured by the automatic generation control (AGC). Power in the tie-line, speed, and frequency of the generator is used as regulating signals that include the area-control-error (ACE) [39][40].

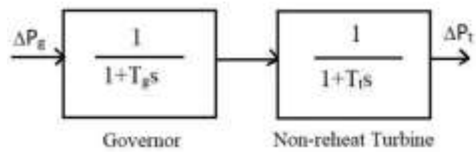

Fig. 1. Turbine along with governor block diagram.

Fig. 2 above shows the interconnected two-area microgrid system which is considered for the present study. The interconnected microgrid system is efficiently used in the investigation of the system for the design and analysis of LFC [41]. The area control errors of interconnected two area microgrid system are denoted by ACE_{M1} and ACE_{M2}; Frequency bias parameters are represented by B_{M1} and B_{M2}; governor speed regulation parameters is represented by R_{M1} and R_{M2}; ΔP_{C1} and ΔP_{C2} show the regulating outputs taken out from the PID controller; T_{12} and T_{21} shows the tie-line synchronizing coefficient; ΔP_{Tie} represents a deviation in tie-line power; time constants of speed governor is denoted by T_{G1} and T_{G2}; H_{M1} and H_{M2} are inertia coefficient; turbine time constant is represented by T_{T1} and T_{T2}; D_{M1} and D_{M2} are damping coefficient; $F_{M1}$and ΔF_{M2} shows frequency deviations of the system in Hz and ΔP_{L1} and ΔP_{L2} shows the change in load demands. The appendix gives the nominal values of the parameters.

3. OBJECTIVE FUNCTION DESIGN AND CONTROL SIGNAL

Performance analysis of interconnected two-area microgrid systems is carried out by optimizing the gain values of the PID controller. In the process industry, the most effective controller for feedback operation is the PID controller. It can give efficient control performance and it is robust despite the continuously varying dynamic behavior of the process plant. A derivative controller is used to ameliorate the transient response, decrease the peak overshoot value, and improve the stability of the microgrid system. To decrease the rise time, a proportional controller is used but it never decreases the steady-state error. To decrease the steady-state error, an integral controller is used but it may degrade the transient response. When stability and fast response are needed, PID controllers are the best choice. Integral-gain-constant (K_I), Derivative-gain-constant (K_D) and Proportional-gain-constant (K_P) are three main parameters that are essential for designing the PID controller. In comparison to other controllers, the advantage of the PID controller is that it can help in improving system stability and also for achieving better settling time [20]. The eq. (1) given below represents the transfer function of the PID controller in the s-domain.

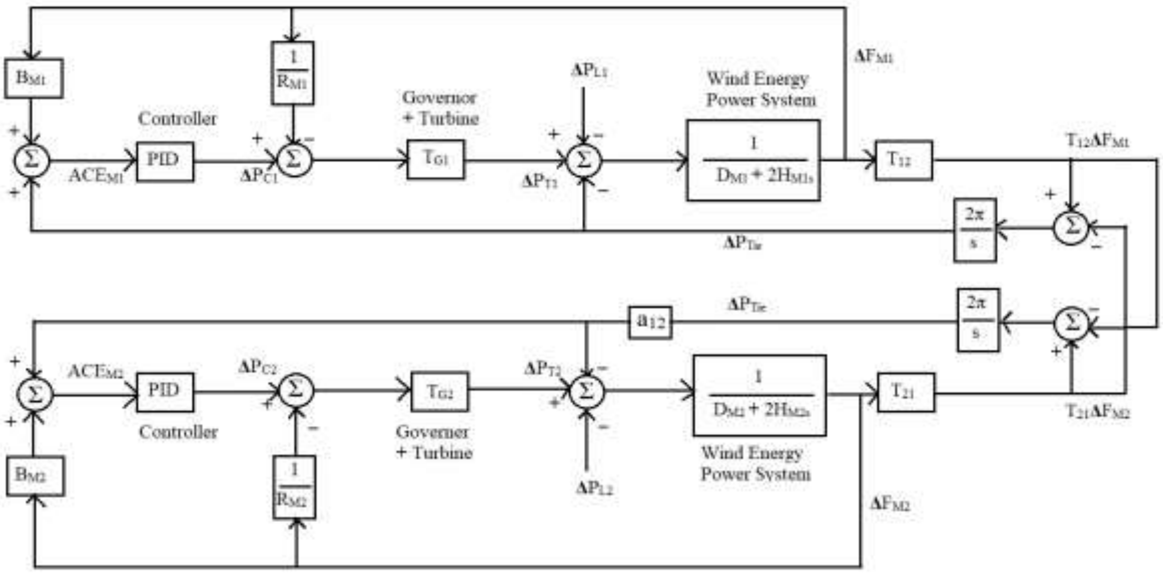

Fig. 2. Interconnected two area microgrid system MATLAB/SIMULINK model**.**

$$TF_{PID} = K_p + \frac{K_I}{s} + K_D s \qquad (1)$$

Area-control errors (ACE) are respectively represented by eq. (2) and (3) and these are fed to the respective controllers as input.

$$e_{M1}(t) = ACE_{M1} = B_{M1}\Delta F_{M1} + \Delta P_{Tie} \qquad (2)$$

$$e_{M2}(t) = ACE_{M2} = B_{M2}\Delta F_{M2} + a_{12}\Delta P_{Tie} \qquad (3)$$

The respective outputs of the PID controller are ΔP_{C1} and ΔP_{C2} and these are used as the regulating inputs of the two interconnected microgrid areas, respectively. To begin with, a controller is designed based on modern heuristic optimization technique according to the desired constraints and specifications and this controller is used to calculate the objective function. ITAE (Integral of Time-multiplied-Absolute-Error), IAE (Integral of Absolute-Error), ITSE (Integral of Time-multiplied-Squared-Error) and ISE (Integral of Squared-Error) are generally used in the control design for performance criteria. ISE, as well as IAE-based tuning, cannot be used for decreasing settling time therefore, the ITAE criterion is used to reduce it. Peak overshoot is also reduced due to the ITAE criterion. It was proved already that ITAE is a preferable fitness function in the case of LFC studies. Thus, an objective function based on the ITAE criterion is used for the optimization of derivative, integral and proportional gain values of the PID controller. The expression for the fitness function based on IAE, ISE, ISE and ITAE criteria for the proposed system is given below in eq. (4), eq. (5), eq. (6) and eq. (7), respectively.

$$IAE = \int_0^{t_{sim}} \left(|\Delta F_{M1}| + |\Delta F_{M2}| + |\Delta P_{Tie}|\right).dt \qquad (4)$$

$$ISE = \int_0^{t_{sim}} \left((\Delta F_{M1})^2 + (\Delta F_{M2})^2 + (\Delta P_{Tie})^2\right).dt \qquad (5)$$

$$ISE = \int_0^{t_{sim}} \left((\Delta F_{M1})^2 + (\Delta F_{M2})^2 + (\Delta P_{Tie})^2\right).t_{sim}.dt \qquad (6)$$

$$Y = ITAE = \int_0^{t_{sim}} \left(|\Delta F_{M1}| + |\Delta F_{M2}| + |\Delta P_{Tie}|\right).t_{sim}.dt \qquad (7)$$

In the above equation, t_{sim} represents the simulation time range. The problem constraints of the above equation are gain values of parameter bounds of the PID controller. Subsequently, the design problem formulation is represented by the following optimization problem.

Minimizes Y

Subjected to $K_{Dmin} \leq K_D \leq K_{Dmax}$, $K_{Imin} \leq K_I \leq K_{Imax}$ and $K_{Pmin} \leq K_P \leq K_{Pmax}$

The constraint set for gain values of PID controller parameters is [0, 5] that is chosen after comprehensive trial and error method.

4. OPTIMIZATION ALGORITHM

4.1. Flower Pollination Algorithm

In 2012, Xin-She Yang suggested the concept of the Flower-Pollination-Algorithm (FPA). Plants that have flowers stick to the pollination process inspired him to propose FPA. For clarification, four basic rules which are used in FPA are given below [34].

- The global pollination process considers cross and biotic pollination, and pollen that carried pollinators takes the path that is according to Levy flights.
- Abiotic and self-pollination avail oneself of local pollination.
- Insects which are an example of pollinators flourish flower fidelity, which is equivalent to the reproduction probability and it is corresponding to the mixing of two flowers in consideration.
- The connection or switching of local and global pollination can be modified by a switch probability $p \in [0, 1]$, somewhat according to local pollination.

4.2. Harmony Search Algorithm

In 2000, Geem suggested the concept of the Harmony-Search-Algorithm (HSA) [29]. At first, he suggested the HS to resolve the optimization problem of water dispersal networks [42]. A few years back, HSA was developed as a new and innovative population-based metaheuristic algorithm, in the field of control, mechanical engineering, signal processing, etc. it has achieved substantial research advancement [43]. In HSA, four principal steps elaborate on the concept of HSA, which are given below:

- Initialization of Harmony Search memory (HM) takes place, the HM is initialized and it consists of several arbitrarily generated results as required by the user to solve the problem of optimization.
- A new solution is improvised from the HM. Each segment of this solution is calculated according to the HMCR. The ambiguity of choosing a constituent from the available arbitrary HM members is called HMCR.
- HM is updated. The fresh solutions from the second step are obtained again. If it provides favorable results of objective function than that of the most unfavorable member in the HM, it will supersede the most unfavorable one, or else, it will be discarded.
- Replicate the second and third steps till the termination criterion is attained.

4.3. Bat Algorithm

In 2010, Xin She Yang suggested the concept of a Bat-algorithm (BA), which is based on a bio-inspired-algorithm and it works very effectively [33]. Micro-bats typically use echolocation which is a type of sonar to avoid obstacles, discover prey, and discover their perch cracks in the absence of light. A sound pulse that is very loud is emitted by them and then listen to their echoes reflected from the neighboring obstacles (Richardson, 2008). The sound pulses which is produced have different properties and can be matched up with their attacking techniques, which depend on one species to another. The three generalized rules of BA are as follows:

- Echolocation is used by all the micro-bats to percept displacement, and they can also distinguish between the background barriers and prey/food mystically;
- Bats fly randomly with a frequency f_{min} at location x_i with velocity v_i, loudness A_0 and varying wavelength λ to hunt for prey. Micro-bats can instinctively change the frequency (or wavelength) of their generated pulses and change the pulse emission rate $r \in [0, 1]$, according to the propinquity of their prey;

Though the loudness produced by them can change in different ways, we consider that the produced loudness changes from a minimum constant value A_{min} to a large (positive) A_0.

5. ANALYSIS OF RESULTS AND SIMULATION

5.1. Result Analysis using MATLAB/Simulink:

In the dynamic performance analysis of interconnected two area microgrid system, the regulating parameters of HSA can be taken as Harmony-Memory-Size (HMS) = 6, Bandwidth-Range = 0.0001-1, Pitch-Adjusting-Range (PAR) = 0.4-0.9 and Harmony-Consideration-Rate (HMCR) = 0.9; the regulating parameters of BA are as follows Loudness = 0.5, Population-size = 20, No. of generations = 100, Pulse-rate = 0.5 and Frequency-range = 0-2; FPA controlled parameters are as follows population-size = 20, probability-switch (p) = 0.8 and maximum-generation = 100. An interconnected two-area microgrid system is contemplated with PID controllers. The model of this system is generated in MATLAB/SIMULINK and the program of HSA, BA, FPA and GA which is considered in this paper is written (in .m file). In the aforementioned work, the gain values are taken as the constraint of the PID controller and it is taken as [-5, 5]. Table 1 below shows the PID controller gain values optimized using HSA, BA, FPA and GA which we have evaluated after running the respective program. The objective function is based on the ITAE criterion which is denoted by Eq. (7) and a 1% increment in step load is applied in the area1 of the developed system and the PID controller's gain values by the respective method are calculated for the developed model by running simulation. The PID controllers gain values optimized using HSA, BA, FPA and GA, and the dynamic characteristics of the respective system are represented by Figs. 3(a)-3(c) and outcomes of the results suggest that the PID controller gain values optimized using HSA offer better dynamic characteristics. Table 2 shows the corresponding performance indicators concerning settling time, peak undershoot and peak overshoot calculated for the tie-line power deviation and frequency deviation of area1 and area 2 of the developed system [44]. Using all of the methods described above, various performance indices have been computed and summarised in Table 3. Along with the commonly used indices of the integral of absolute error (IAE), integral of time squared error (ITSE) and integral of squared error (ISE), the comparison also uses the ITAE. In comparison to the other described optimizing strategies, the gain values of the HSA optimized PID controller produce better results for the performance indices ITAE, ITSE, ISE, and IAE. The estimated indices demonstrate that the HSA method is superior to the others. [40][45][46].

Table 1. Optimal PID controller gain values by different optimization techniques.

Controller/ Parameters	*HSA*	*BA*	*FPA*	*GA*
K_P	4.24	2.87	4.54	4.87
K_I	4.92	3.34	4.83	4.95
K_D	2.72	1.42	1.78	1.98

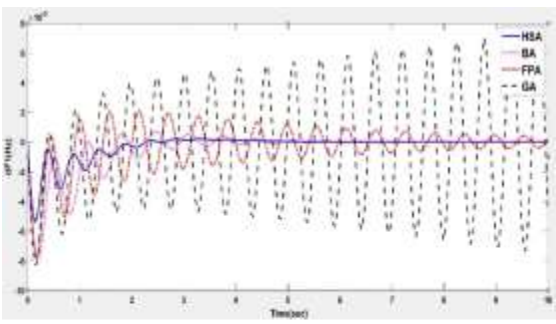

Fig. 3(a). Fluctuation in Frequency in area 1 for 1% SLP in area 1.

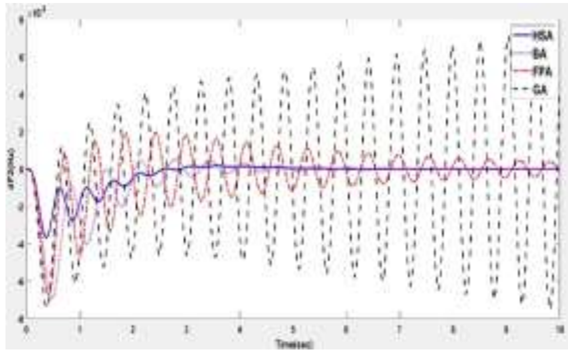

Fig. 3(b). Fluctuation in Frequency in area 2 for 1% SLP in area 1.

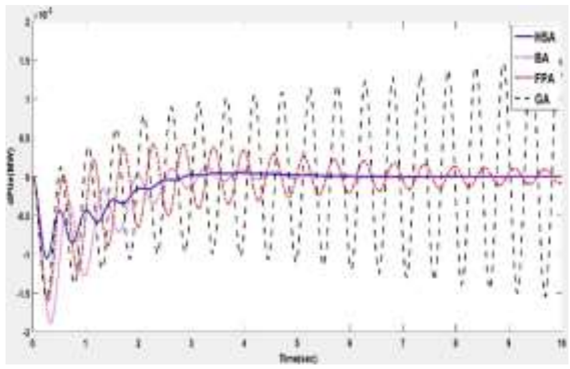

Fig. 3(c). Deviation in the line power 1% SLP in area 1.

Table 2. Transient performance of optimized PID controllers for different techniques.

Controller/ Parameters	Peak undershoot x 10^{-3}			Peak overshoot x 10^{-3}			Settling time(sec) x 10^{2}		
	ΔF_{M1} (Hz)	ΔF_{M2} (Hz)	ΔP_{Tie} (MW)	ΔF_{M1} (Hz)	ΔF_{M2} (Hz)	ΔP_{Tie} (MW)	ΔF_{M1}	ΔF_{M2}	ΔP_{Tie}
HSA	-5.4	-3.7	-1.1	-0.5	-1.1	-0.4	1.29	1.49	1.59
BA	-7.9	-6.9	-1.9	-0.9	-1.0	-0.3	1.44	1.54	1.67
FPA	-7.8	-6.7	-1.6	0.4	0.8	0.1	3.11	3.12	3.09
GA	-8.3	-7.5	-1.6	0.5	1.1	0.2	Values Diverging due to over-damped response		

Table 3. System performance evaluation with the different criterion for different heuristic-based optimized PID controller.

Controller/ Parameters	ITAE	ITSE	IAE	ISE
HSA	0.2716	0.0002	0.2527	0.0004
BA	0.4815	0.0008	0.4127	0.0013
FPA	2.0928	0.0022	0.7064	0.0016
GA	13.3637	0.0609	2.4455	0.0105

5.2. Result Analysis using OPAL-RT

On an FPGA-based OPAL-RT (OP-5700) as shown in Fig.4, real-time simulation is conducted with HIL. In HIL simulation, a computer model that is identical to the physical plant that interfaces with other equipment and control systems replace the physical plant. The simulation time in real-time simulation is independent of the host PC's timer. Its timer is in sync with an actual clock. A fixed time step is used in real-time simulation. At least two subsystems are required for any model that runs in OPAL-RT. The console connects to the engineering PC in real-time, while the master is synced in real-time. The console subsystem has been created to enable the user to interact with the model parameters in real-time while viewing the signals through DSO. The same PID controllers gain values optimized using HSA, BA, FPA and GA taken in the case of OPAL-RT simulation, and the dynamic characteristics response of the respective system are represented by Figs. 5(a)-5(c) and outcomes of the results suggest that the PID controller gain values optimized using HSA offer better dynamic characteristics. Table 4 shows the corresponding performance indicators concerning peak undershoot and peak overshoot calculated for the deviation in the tie-line power and fluctuation in the frequency of area1 and area 2 of the developed system in the case of OPAL-RT simulation.

Fig. 4. OPAL-RT (OP5700) Laboratory setup.

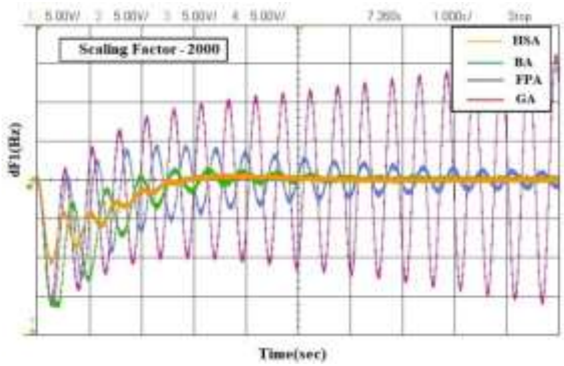

Fig. 5(a). Fluctuation in Frequency in area 1 for 1% SLP in area 1.

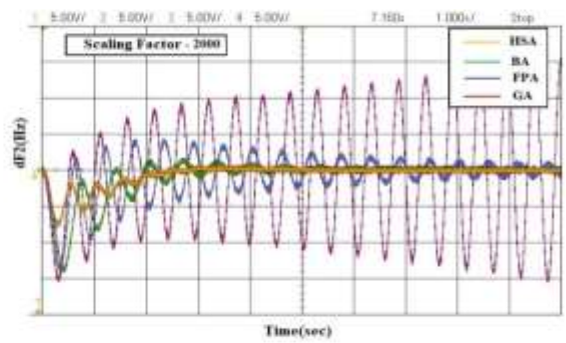

Fig. 5(b). Fluctuation in Frequency in area 2 for 1% SLP in area 1.

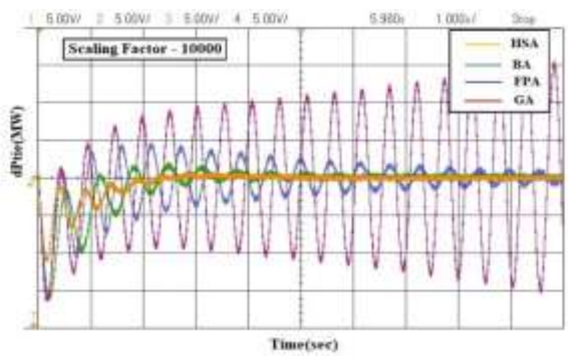

Fig. 5(c). Deviation in the tie line power for 1% SLP in area 1.

Table 4. Transient performance of optimized PID controllers for different techniques in real-time.

Controller/ Parameters	Peak undershoot x 10^{-3}			Peak overshoot x 10^{-3}		
	ΔF_{M1} (Hz)	ΔF_{M2} (Hz)	ΔP_{Tie} (MW)	ΔF_{M1} (Hz)	ΔF_{M2} (Hz)	ΔP_{Tie} (MW)
HSA	-5.1	-3.5	-1.1	-1.8	-1.0	-0.1
BA	-7.6	-7.0	-1.6	-1.4	-0.8	-0.2
FPA	-8.0	-6.8	-1.6	0.4	0.9	0.1
GA	-8.5	-7.5	-1.7	0.6	1.2	0.2

5.3. In-depth Analysis

To indicate the rigorousness of the proportional-integral-derivative controller, modification is done in area 1 by 1-3% SLP. The gain values of the PID controller optimized using HSA show better dynamic performance in comparison to other techniques used in this research proposal. Consequently, the dynamic characteristics analysis of PID controller gain value optimized using HSA of the two-area interconnected microgrid system for 1-3% SLP values in case of MATLAB/SIMULINK are represented in the Figs. 6(a)-6(c) and in the case of OPAL-RT (OP5700) simulation is represented in Figs. 7(a)-7(c). The results obtained after dynamic performance analysis suggests clearly that the HSA optimized PID controller responds satisfying to varying load disturbances.

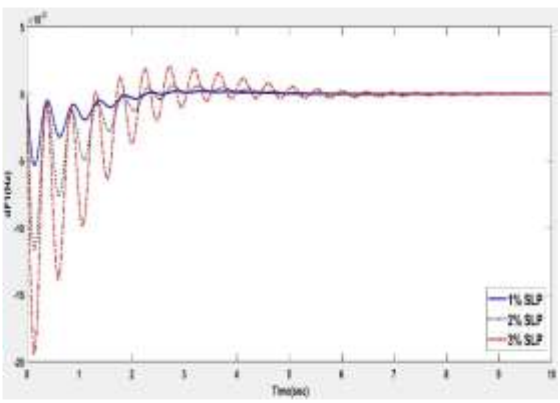

Fig. 6(a). Fluctuation in frequency area 1 for 1-3% SLP in area 1 using HAS.

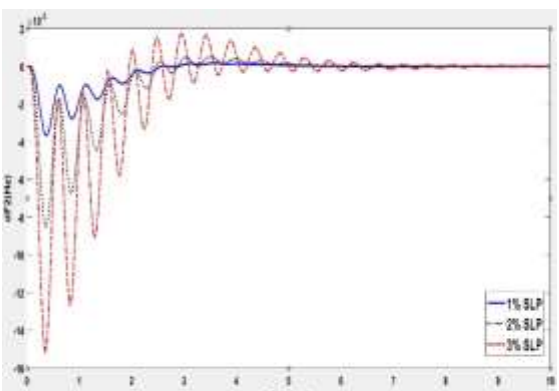

Fig. 6(b). Fluctuation in frequency in area 2 for 1-3% SLP in area 1 using HAS.

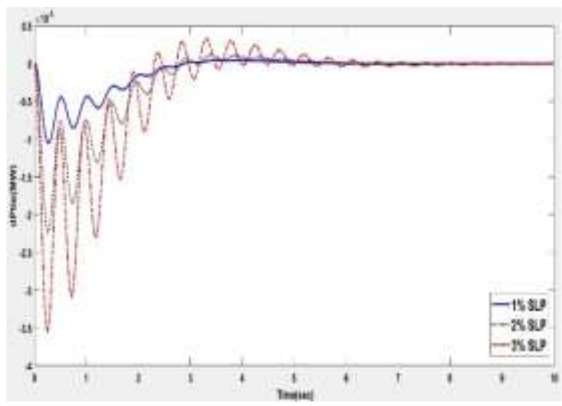

Fig. 6(c). Tie line power deviation for 1-3% SLP in area 1 using HAS.

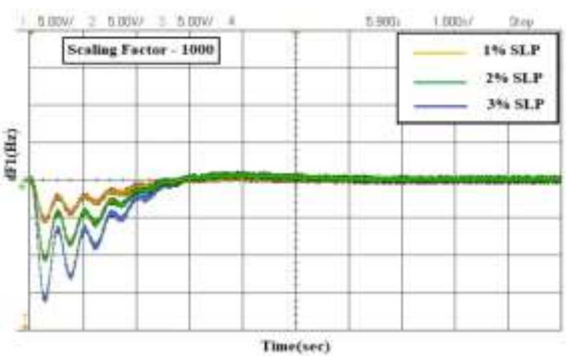

Fig. 7(a). Fluctuation in frequency in area 1 for 1-3% SLP in area 1 using HAS.

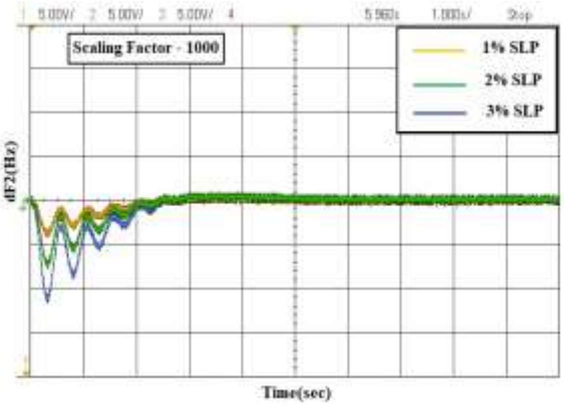

Fig. 7(b). Fluctuation in frequency area 2 for 1-3% SLP in area 1 using HAS.

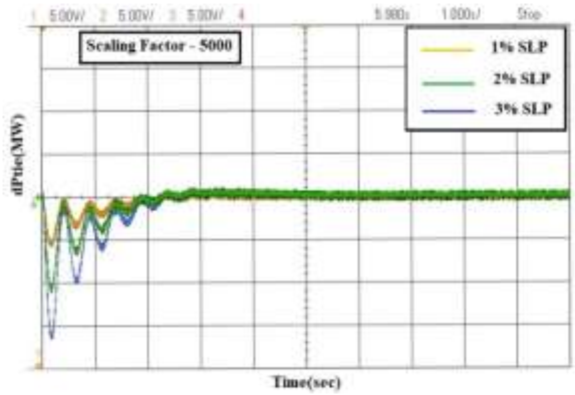

Fig. 7(c). Tie line power deviation for 1-3% SLP in area 1 using HAS.

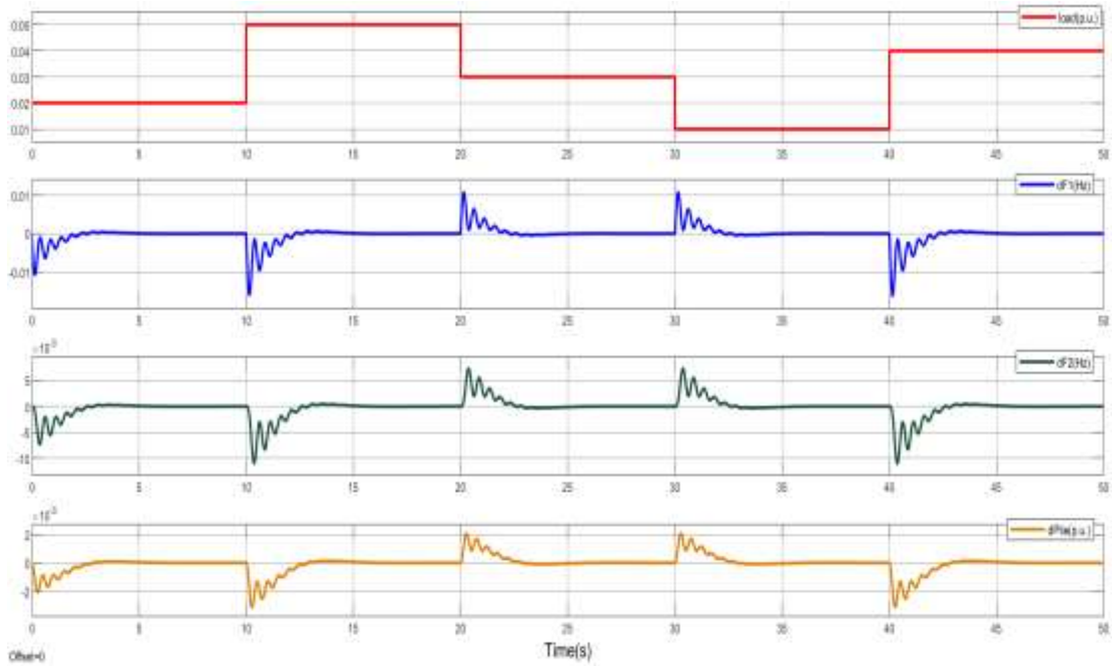

Fig. 8. Dynamic responses under random step load pattern in area 1, tie-line power deviation (dPtie), frequency deviation in area 1 (dF1) and frequency deviation in area 2 (dF2).

5.4. Random Step Load Pattern

To perform additional analysis, the PID controller gain value optimized using HSA of the two-area interconnected microgrid system is applied to a random step load pattern (RSLP) in area 1 and the dynamic characteristics responses of the controller are obtained in MATLAB/SIMULINK given in Fig. 8. PID controller gain values optimized with the help of HSA technique value provide enhanced system stability. Also, the figures demonstrate the beneficial effect in terms of reduced frequency peak and variations and tie-line power deviations.

6. CONCLUSION

The work proposed in this research work contemplates the use of several metaheuristic optimization algorithm to optimize the gain values of PID controller for the LFC problem of an interconnected microgrid system, including the Flower Pollination Algorithm (FPA), Bat-Algorithm (BA), Harmony Search Algorithm (HSA) and Genetic Algorithm (GA). Results obtained after simulating the proposed system in MATLAB/Simulink and HIL on an FPGA-based real-time simulator (OP5700) suggest that there is a notable enhancement in dynamic characteristics of the system in terms of settling time, peak undershoot and peak overshoot in case of HSA optimized gains value of PID controller. Since, HSA optimized PID controller shows a better result, therefore the proposed system is analyzed in presence of 1%-3% SLP values and RSLP. The results obtained after dynamic performance analysis suggest clearly that the HSA optimized PID controller responds satisfactorily to varying load disturbances.

7. APPENDIX

Nominal parameters of the two-area interconnected microgrid system:

$B_{M1} = B_{M2} = 0.315$ p.u.MW/Hz; $R_{M1} = R_{M2} = 3.33$ Hz/p.u.; $T_{T1} = T_{T2} = 0.4$ sec; $T_{G1} = T_{G1} = 0.08$ sec; $H_{M1} = H_{M2} = 0.075$ p.u.sec; $D_{M1} = D_{M2} = 0.015$; $T_{12} = T_{21} = 0.2$; $a_{12} = -1$.

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