Comparative Study of Optimization Techniques and Fuzzy Logic Controller for Load Frequency Control in Hybrid Power System

2023 IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation (SEFET) | 979-8-3503-1997-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/SEFET57834.2023.10245520

S V Harshavardhana Hemanth Brahmarapu
Department of Electrical Engineering
National Institute of Technology
Warangal, India
sbee21217@student.nitw.ac.in

Dr. Altaf Q H Badar
Department of Electrical Engineering
National Institute of Technology
Warangal, India
altafbadar@nitw.ac.in

***Abstract*—This study focuses on the Load Frequency Control (LFC) of an islanded Hybrid Power System (HPS) that comprises a Wind Energy System (WES), a Diesel Energy System (DES), and a Superconducting Magnetic Energy Storage System (SMES). The study presents the implementation of the latest optimization techniques and the conventional Fuzzy Logic Controller (FLC) to improve the profiles of power and frequency in the HPS. The optimized control parameters of Proportional-Integral-Derivative (PID) using five different optimization techniques namely Runge-Kutta Optimization (RUN), Reptile Search Algorithm (RSA), Particle Swarm Optimization (PSO), Ant-Lion Optimization (ALO), and Artificial Bee Colony (ABC) are presented. The controllers for the WES and the DES were employed to control the power output and frequency. The SMES is utilized to enhance the system's power quality. A comparative analysis of the five optimization techniques and the FLC in terms of power and frequency control, time, and speed of optimization is presented. The results of the study show that the implementation of optimization techniques for LFC in an islanded HPS can effectively improve the power and frequency profiles of the system. The comparative analysis provides insights into the most effective optimization techniques for LFC in HPS.**

Keywords—Load Frequency Control, Hybrid Power System, RUN, RSA, ABC, ALO, PSO, FLC

I. Introduction

The electricity demand is increasing day by day but the fossil fuels required for the generation are diminishing [1]. Along with this, these fossil fuels have a negative impact on the environment [2]. In most of the developing economies, the major source of electricity for islanded areas is Diesel Engine generators. Due to the remoteness of these islanded areas, the transportation of fuel, and storage of fuel make the fuel cost higher. In Islands, hills, and places where sufficient wind speed is not present, Wind-Diesel based HPS is economically more feasible [3], [4]. In this study, an HPS consisting of a DES, and a WES is proposed. To enhance the system's power quality, SMES is used in the system. The addition of multiple sources makes the system complex which in turn results in its instability whenever a sudden and large disturbance in load occurs. In these cases, the LFC is utilized with the primary goal of minimizing transient error variations in both the power and the frequency and ensuring that these variables have zero steady-state errors. Due to this, the complexity of HPS is increased and made the LFC challenging. So, an effective control strategy is needed for this purpose. In the past, several optimization techniques were implemented for LFC by tuning the PID controller gain parameters [5].

In this study, the latest optimization techniques like Runge-Kutta Optimization (RUN) [6], Reptile Search Algorithm (RSA) [7], and the most popular algorithms like Particle Swarm Optimization (PSO) [8], Ant-Lion Optimization (ALO) [9], and Artificial Bee Colony Optimization (ABC) [10], [11] are implemented for tuning the PID controller gain parameters. Comparative Analysis for each optimization technique along with the conventional FLC has been done in terms of power and frequency profiles such as overshoot, undershoot, settling time, and in terms of speed of optimization.

II. System Model

In general, hybrid energy systems offer improved energy stability since different power sources are connected to them which leads to increased sustainability. In the present study, the Island HPS consists of a DES, a WES, and a SMES System. The whole structural configuration is shown in Fig. 1 which consists of individual controllers for both the DES and the WES. A brief description of each of these systems is given as follows:

A. Diesel Generator Transfer Function Model

The Diesel Generator detects the demand variations of an HPS, and the fuel management is carried out by the control mechanism. The diesel generator consists of a turbine, a governor, and a speed control loop. The amount of fuel injected into the cylinders is regulated by the governor, thereby controlling the diesel engine speed.

The transfer function of the governor and diesel engine turbine equations are written as follows:

$$G_g(s) = \frac{1}{1+sT_g} \tag{1}$$

$$G_t(s) = \frac{1}{1+sT_t} \tag{2}$$

where Tg is the governor's time constant, and T_t is the time constant of the turbine.

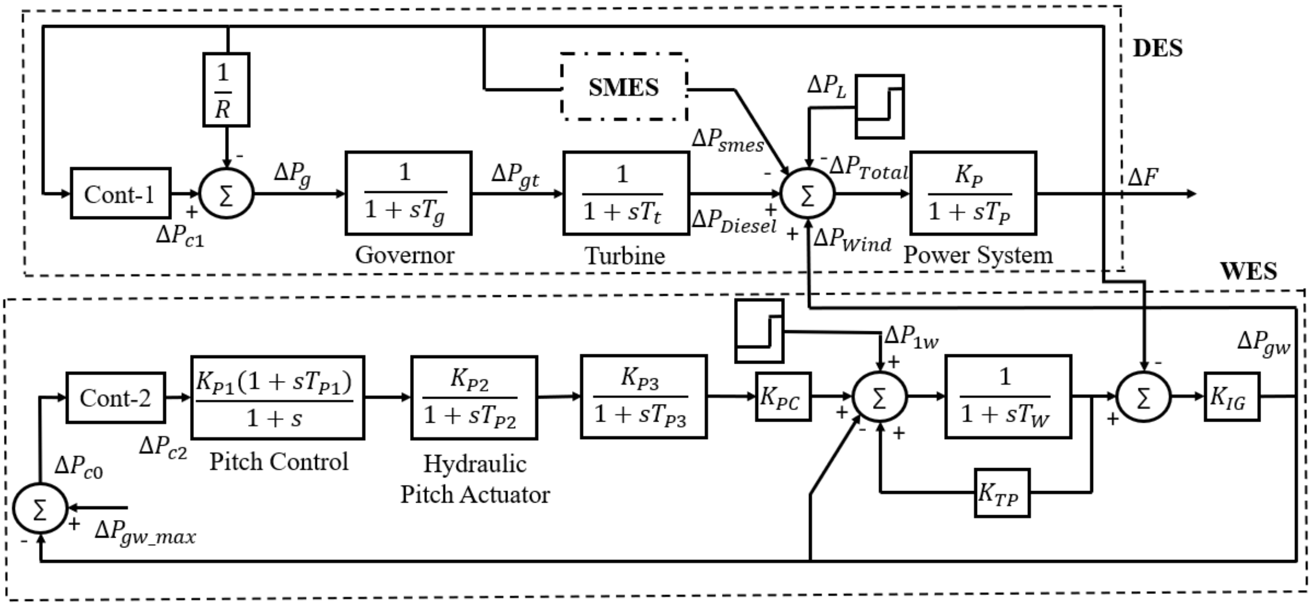

Fig. 1. Transfer Function Model of HPS

The governor controller takes the frequency change of the HPS as an input signal and gives the controlled output signal.

$$\Delta P_g = \Delta P_{c1} - \frac{\Delta F}{R} \quad (3)$$

$$\Delta P_{c1} = \Delta F[C_1] \quad (4)$$

Where ΔP_g is the input deviation to the governor, ΔP_{c1} is the output from controller-1 sent to the governor of the DES and ΔF is the frequency deviation.

B. Wind Turbine Transfer Function Model

A WES consists of several parts, including a turbine, blades, gearing, and generator. The wind turbine is coupled with a gearbox which converts the lower speeds into higher speed that is required for the generators to generate the power. The amount of power that is being transformed is managed by the blade pitch angle controller. The pitch mechanism technique is employed for controlling power output from a wind turbine generator. The pitch controller keeps track of the turbine's start and halt, power-making optimization, and speed control. From Fig. 1 the control equations for the pitch controller are written as:

$$\Delta P_{c0} = P_{gw\_max} - P_{gw} \quad (5)$$

$$\Delta P_{c2} = \Delta P_{c0}[C_2] \quad (6)$$

ΔP_{c2} is the deviation in controller-2 output to the turbine of the WES and ΔP_{c0} is the error signal from the speed regulator of WES.

C. SMES Model

SMES consists of a transformer, a power-controller unit, and a superconducting coil. The superconducting coil stores the energy in the form of a magnetic field whenever current flows through it. Operating this coil at cryogenic temperatures between 20K and 77K causes it to become superconducting. When temperatures drop below a cryogenic threshold, there are lower electric losses. The charging and discharging of SMES are managed by the commutation angle of the converter. The converter will work in charging mode when the angle is set to 90 degrees, and in discharging mode if it is set to greater than 90 degrees. The simplified control system for SMES is illustrated in Fig. 2. The SMES controller uses the change in frequency as an input. For the SMES unit to promptly restore its energy levels and inductor current, the current deviation of the inductor is measured and supplied back to the control loop as a negative signal. This helps the system be prepared to respond to any further disturbance.

The equations for deviation in DC voltage, current, and output power from the SMES system are shown below:

$$\Delta E_{sm} = \left(-K_{sm}\Delta I_{sm} + K_f \Delta F\right)\left(\frac{1}{1+sT_{dc}}\right) \quad (5)$$

$$\Delta I_{sm} = \Delta E_{sm}\left(\frac{1}{sL}\right) \quad (6)$$

$$\Delta P_{smes} = \Delta E_{sm}\Delta I_{sm} + \Delta E_{sm}\Delta I_{sm0} \quad (7)$$

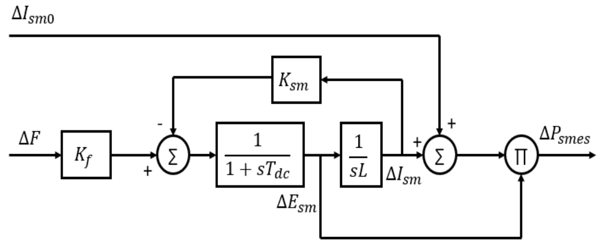

Fig. 2. SMES Transfer function model

III. Control Methodology

From Fig. 1, The following equation gives the change in total power output for the island HPS.

$$\Delta P_{Total} = \Delta P_{Diesel} + \Delta P_{Wind} \pm \Delta P_{smes} - \Delta P_L \quad (8)$$

ΔP_{Diesel} is the total power deviation of the DES, ΔP_{Wind} is the deviation in the total power of the WES, ΔP_{smes} is the deviation in the output power of the SMES unit and ΔP_L is the change in load demand.

The state space representation of the HPS can be expressed as:

$$\dot{X} = [A]X(t) + [B]U(t) + [L]D(t) \quad (9)$$

$$Y = [C]X(t) \quad (10)$$

where A is the system matrix, B is the input distribution matrix, L is the disturbance distribution matrix, $X(t)$ is the state vector, $U(t)$ is the control vector, $D(t)$ is the disturbance vector and $Y(t)$ is the output vector.

The state vector and the disturbance vector for the considered system are given below:

$$\dot{X}(t) = [\Delta F \ \Delta P_{Total} \ \Delta P_{Diesel} \ \Delta P_{gt} \ \Delta P_g \ \Delta P_{c1} \ \Delta P_{smes} \ \Delta F_T \ \Delta P_{gw} \ \Delta P_{c2} \ \Delta P_{c0}] ; \quad (11)$$

$$U(t) = [U_1 \ U_2]^T \quad (12)$$

$$D(t) = [D_1 \ D_2]^T = [\Delta P_L \ \Delta P_{iw}] \quad (13)$$

$$Y(t) = X_1 = \Delta F \quad (14)$$

A. Fuzzy Logic Controller (FLC)

In this study, a conventional FLC is implemented for LFC. The Mamdani fuzzy inference engine is chosen for this FLC. In this, five triangular membership functions (MFs) are used to implement the inference mechanism for each of the three linguistic variables of each controller.

The first controller is considered to have two inputs: ΔF and its derivative. The output ΔP_{c1} of this controller is sent to the diesel generator's governor. The second controller is considered to have two inputs: ΔP_{c0} and its derivative. The output ΔP_{c2} of this controller is sent to the pitch controller of the wind turbine.

These FLC's outputs, such as P_{c1} and P_{c2}, act as control inputs to the governor and the pitch controller respectively. Table 1 depicts the if-then rules for these FLCs and the membership functions are illustrated in Fig. 3.

Table 1. If-then rules of FLC

		Derivative of Error				
		BN	***LN***	***Z***	***LP***	***BP***
Error	***BN***	BN	BN	BN	LN	Z
	LN	BN	BN	LN	Z	LP
	Z	BN	LN	Z	LP	BP
	LP	LN	Z	LP	BP	BP
	BP	Z	LP	BP	BP	BP

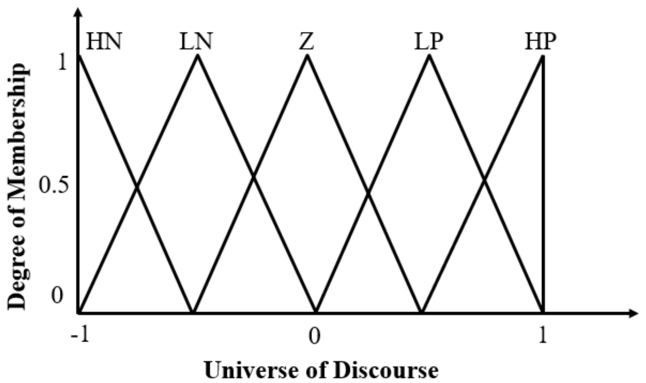

Fig. 3. Membership Functions of FLCs

Where BN is Big Negative, LN is Low Negative, Z is Zero, LP is Low Positive, and BP is Big Positive.

Along with this FLC five optimization techniques that are used for tuning the PID controller parameters are discussed below.

B. Artificial Bee Colony (ABC) Optimization

ABC optimization is a population-based technique that was motivated by honey bee behavior. An artificial bee colony is used in the ABC algorithm to search the search space for the best solution.

In this algorithm, three types of bees search the space in three different phases: (i) employed bee phase, (ii) onlooker bee phase, and (iii) scout bee phase. Employed bees search the space by exploiting the information available from the current best solutions. Onlooker bees choose the food sources based on the quality of the solutions found by employed bees. Scout bees explore new areas of the search space by randomly selecting solutions.

C. Particle Swarm Optimization (PSO)

PSO is another optimization algorithm that is population-based. This technique mimics the social behavior of a fish school or a flock of birds. In the PSO method, a swarm of particles navigates the search space using both the best positions of the swarm and their individual best positions.

Every particle in the swarm stands for a possible solution to the problem, which is to be optimized, and its position and velocity are updated based on the experience of swarm and its own experience. The algorithm iteratively refines the positions of the particles until it converges to the optimal solution.

D. Ant Lion Optimization (ALO)

ALO is an optimization technique inspired by nature, based on the hunting behavior of antlions. Antlions are predators that wait for ants to fall into their traps. In the sand, they create cone-shaped trenches, and at the bottom, they wait for an ant to fall in. An ant that falls into the pit is attacked and eaten by the antlion. The antlion prepares a new pit to catch the next prey after consuming the last one. This hunting activity can be broken down into five stages: (i) ant's random walk, (ii) trap building, (iii) ant entrapment in traps, (iv) prey capture, and (v) trap re-building.

E. Reptile Search Algorithm (RSA)

RSA is a metaheuristic algorithm inspired by crocodile hunting techniques. The RSA includes initialization, global search, and local search stages. It is a gradient-free practice that can be employed to solve both simple and complex tasks which need to be optimized under given constraints. This population-based algorithm is implemented in three steps: (i) Initialization phase, (ii) Encircling phase (Exploration), and (iii) Hunting phase (Exploitation).

F. Runge (RUN) Kutta-based Optimization

RUN is a metaphor-free algorithm that uses the concept of slope variations obtained by the Runge-Kutta 4 (RK4) technique for global optimization as a logical approach. For exploring the viable locations in the search space, this technique employs two efficient phases of exploration and exploitation. To escape the local optimum and accelerate convergence, an enhanced solution quality (ESQ) method is used. This algorithm is described in four stages: (i) Initialization, (ii) Root of Search Mechanism, (iii) Updating solutions, (iv) Enhanced Solution Quality (ESQ).

IV. Results and Discussion

For the implementation of the LFC to the HPS shown in Fig. 1, MATLAB Simulink is used. With an increase of 1% in step load demand, the performance of the FLC and implemented optimization techniques in controlling frequency and power are examined for HPS. The deviation in frequency and wind power with the implemented control techniques are presented in Fig. 4 to Fig. 9. The comparison graphs for both deviation in frequency and wind power are depicted in Fig. 10 and Fig. 11 respectively.

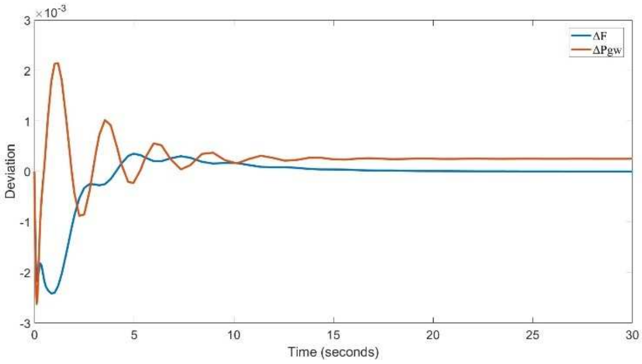

Fig. 4. Deviation in Frequency and Wind Power (pu) with FLC

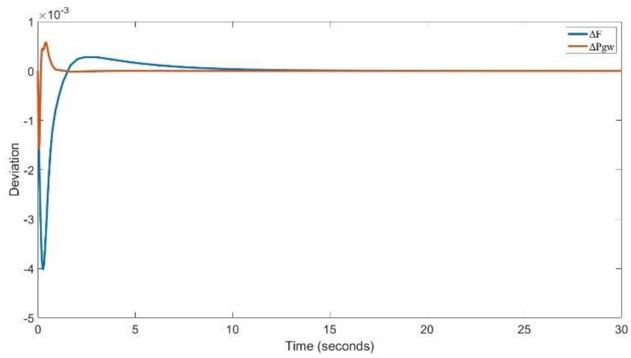

Fig. 5. Deviation in Frequency and Wind Power (pu) with ABC

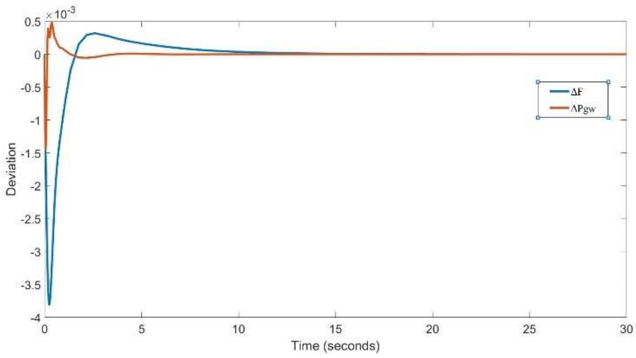

Fig. 6. Deviation in Frequency and Wind Power (pu) with PSO

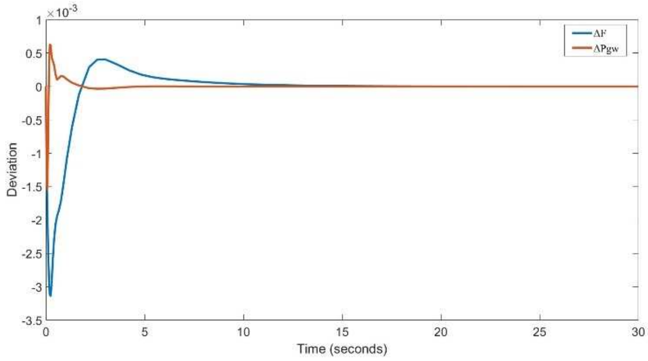

Fig. 7. Deviation in Frequency and Wind Power (pu) with ALO

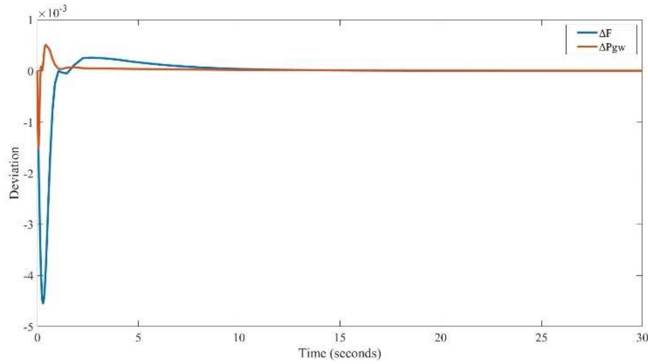

Fig. 8. Deviation in Frequency and Wind Power (pu) with RSA

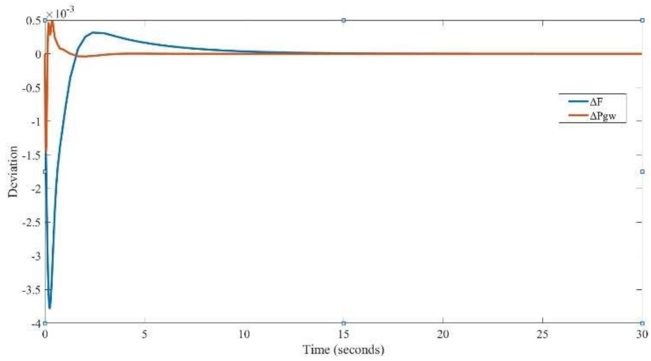

Fig. 9. Deviation in Frequency and Wind Power (pu) with RUN

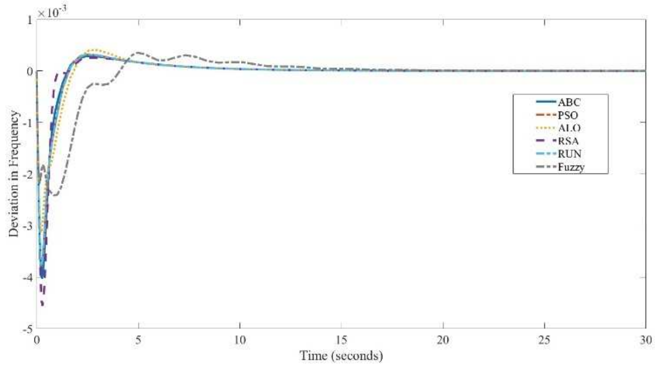

Fig. 10. Deviation in Frequency with all control techniques

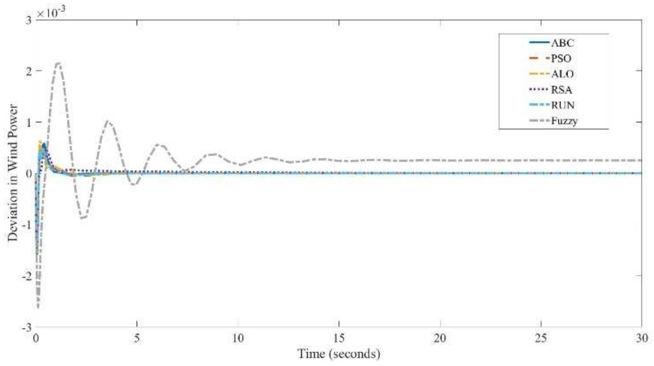

Fig. 11. Deviation in Wind Power with all control techniques

The optimized gain parameters for both the controllers (one is for DES and another for WES) are presented in Table. 2. For each control strategy, comparison parameters like Integral Square Error (ISE), Integral Time Square Error (ITSE), and Integral Average Error (IAE) are presented in the Table. 3 and Table. 4. The Settling time, and Overshoot, Undershoot for the same are presented in Table. 5. The time of optimization (of PID gain parameters) of each optimization technique (for 50 iterations) in the LFC case is presented in Fig. 12.

From these results, we can observe that the use of optimization techniques in the LFC problem improves the system performance in terms of stability of HPS and maintaining the profiles of power and frequency in HPS. Since the design of an FLC is complex, more time is required to obtain effective results. It can be seen from the comparison outcomes that the RUN is the effective optimization technique in terms of minimum deviation of frequency and power, lesser settling time, lesser overshoot, and undershoot. PSO is found to be effective in terms of speed of optimization.

Table 2. Optimized gain parameters of PID controllers.

	Optimization techniques				
Controller-1	**ABC**	**PSO**	**ALO**	**RSA**	**RUN**
K_P	10	10	10	9.8384	10
K_I	10	10	10	9.9571	10
K_D	2.3758	2.70793	3.89005	1.6843	2.77457
	Optimization techniques				
Controller-1	**ABC**	**PSO**	**ALO**	**RSA**	**RUN**
K_P	8.58048	7.42238	5.96322	4.2357	9.40888
K_I	3.79367	10	4.47697	0.4882	9.28193
K_D	3.86027	4.89232	3.79644	4.7363	4.81345

Table 3. ITSE, ISE, and IAE for ΔF

	ΔF		
Algorithm	**ITSE**	**ISE**	**IAE**
ABC	3.093e-06	6.399e-06	0.003644
PSO	3.098e-06	5.993e-06	0.003696
ALO	3.45e-06	5.167e-06	0.003788
RSA	3.352e-06	7.716e-06	0.003509
RUN	3.1e-06	5.927e-06	0.003725
Fuzzy	1.048e-05	8.461e-06	0.006396

Table 4. ITSE, ISE, and IAE for ΔP_{gw}

	ΔP_{gw}		
Algorithm	**ITSE**	**ISE**	**IAE**
ABC	5.102e-08	2.763e-07	0.0003913
PSO	4.016e-08	1.987e-07	0.0004005
ALO	4.36e-08	2.416e-07	0.0004389
RSA	1.206e-07	2.561e-07	0.0008121
RUN	3.368e-08	1.965e-07	0.0003592
Fuzzy	3.623e-05	7.203e-06	0.01042

Table 5. Settling time, Overshoot, and Undershoot of ΔF

	ΔF		
Algorithm	**Settling time**	**Overshoot** $(\times 10^{-4})$	**Undershoot** $-(\times 10^{-3})$
ABC	14.293	3.2326	46.142
PSO	14.293	3.6784	43.792
ALO	14.234	4.7461	36.657
RSA	14.332	3.2874	58.595
RUN	14.219	3.1325	33.512
Fuzzy	19.400	8.8053	55.500

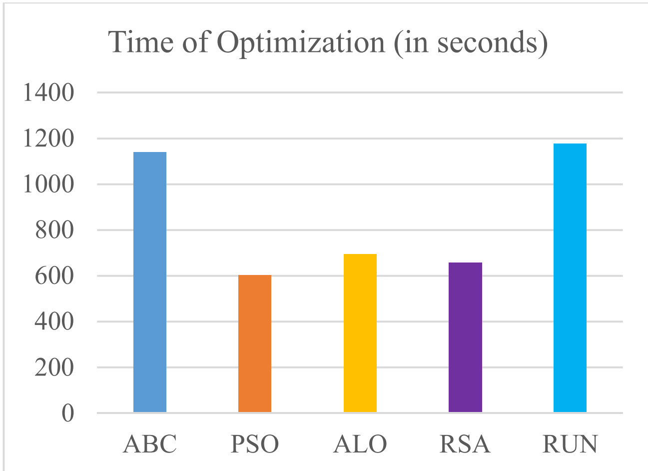

Fig. 12. Time of Optimization (in seconds)

V. Conclusion

In this paper, LFC was implemented by a conventional FLC and five optimization techniques which are used for tuning the gain parameters of the PID controllers used for the DES and WES of an HPS. The results show that the use of optimization techniques in LFC improves the power and frequency profiles. A comparative analysis was carried out with each optimization technique that had been implemented. It was observed that the use of the RUN optimization technique effectively improves the system performance in terms of the lesser deviation of frequency and power, lesser settling time, minimum overshoot, and undershoot. It was also found that PSO is the fastest in tuning the PID gain parameters in the LFC case among other optimization techniques.

VI. Appendix

DES parameters

$T_g = 0.08s; T_t = 0.3s;$

$K_p = 60; T_P = 20s$

WES parameters

$K_{p1} = 1.25; K_{p2} = 1.0; K_{p3} = 1.4; T_{p1} = 0.6s;$

$T_{p2} = 0.041s; T_{p3} = 1.0s; K_{PC} = 0.08; T_w = 4s;$

$K_{IG} = 1.494; K_{TP} = 0.04$

SMES system parameters

$L = 2.5H; T_{dc} = 0.03s; K_{sm} = 0.2\ kV/kA$

References

[1] He, Y.; Guo, S.; Zhou, J.; Wu, F.; Huang, J.; Pei, H. "The quantitative techno-economic comparisons and multi-objective capacity optimization of wind-photovoltaic hybrid power system considering different energy storage technologies". Energy Convers. Manag. 2021, 229, 113779.

[2] Borenstein, S. "The Private and Public Economics of Renewable Electricity Generation." J. Econ. Perspect. 2012, 26, 67–92.

[3] Mbungu, N.T.; Naidoo, R.M.; Bansal, R.C.; Siti, M.W.; Tungadio, D.H. "An overview of renewable energy resources and grid integration for commercial building applications." J. Energy Storage 2020, 29, 101385.

[4] Kumar, Neelamsetti & Gopi, Rahul & Kuppusamy, Ramya & Nikolovski, Srete & Teekaraman, Yuvaraja & Indragandhi, V. & Venkateswarulu, Siripireddy. (2022). "Fuzzy Logic-Based Load Frequency Control in an Island Hybrid Power System Model Using Artificial Bee Colony Optimization". Energies. 15. 2199. 10.3390/en15062199.

[5] Rajamand, S. "Load frequency control and dynamic response improvement using energy storage and modeling of uncertainty in renewable distributed generators." J. Energy Storage 2021, 37, 102467.

[6] I. Ahmadianfar, A. A. Haidari, A. H. Gandomi, X. Chu and H. Chen, "RUN beyond the metaphor: An efficient optimization algorithm based on Runge Kutta method," Expert Syst. Appl., vol. 181, p. 115079, 2021.

[7] L. Abualigah, M. A. Elaziz, P. Sumari, Z. W. Geem, and A. H. Gandomi, "Reptile Search Algorithm (RSA): A nature-inspired metaheuristic optimizer," Expert Syst. Appl., p. 116158, Nov. 2021, doi: 10.1016/j.eswa.2021.116158.

[8] R.C.Eberhart and Y.Shi," Comparison between genetic algorithms and particle swarm optimization," in Proc. IEEE Int. Conf. Evol. Comput., Anchorage, AK, May 1998, pp. 611–616.

[9] Seyedali Mirjalili, "The Ant Lion Optimizer, Advances in Engineering Software," Volume 83, 2015, Pages 80-98, ISSN 0965-9978.

[10] Karaboga, D.; Basturk, B. "A powerful and efficient algorithm for numerical function optimization: Artificial bee colony (ABC) algorithm." J. Global Optim. 2007, 39, 459–471.

[11] Badar, Altaf QH. "Evolutionary Optimization Algorithms." CRC Press, 2021