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Frequency Stability of Multi-source Power System using Whale Optimization Algorithm

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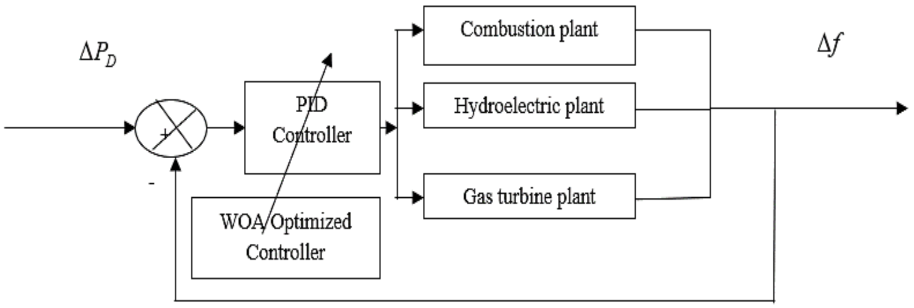
ABSTRACT- The Whale Optimization Algorithm (WOA), an evolutionary computing approach, is presented in this study and is used to auto regulated frequency of many composed power systems including thermoelectric power station, hydroelectric, and gas power plants. The purpose of this process follows the concept of a hunting mechanism of fish through water bubbles. The WOA is first applied to a single region with a multi-source power system for optimal gain adjustment of proportional integral controllers (PID). This approach is then applied to two areas, each having six generating sources with AC and AC-DC links. The credible achievements of the WOA-based PID controller are compared with previously constructed optimization approaches like Teaching Learning Based Optimization (TLBO), Differential evolution (DE) and Optimal Controller (OC), which is demonstrated in terms of frequency error, settling time and damping ratio. The performance indices of the purposed controller are analyzed through different objective functions like integral square error (ISE), integral time absolute error (ITAE), integral absolute error (IAE) and integral time squared error (ITSE)). By using step load agitation, the simulation results indicate that the suggested technique is computationally stable.

Keywords: Load Frequency Control (LFC), HVDC power system, diverse Source System, Performance indices, Whale Optimization Algorithm (WOA).

Graphical Abstract:



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1. INTRODUCTION

The load frequency control (LFC) is an essential component of contemporary power systems. The goal of LFC is to provide high-quality electricity to consumers with no variations in frequency or terminal voltage. The system's energy equilibrium maintains a power balance between supply and demand. Under anomalous load disturbances, the load frequency control entertains a crucial role in keeping the system's frequency and tie-line power within acceptable parameters. In practice, coherent group units are addressed by a number of regions or control zones in power plants that use a combination of thermal, hydro, gas, and non-conventional sources. The regulated output of automated production control (APC) becomes zero when variations in system frequency and chain line power in control regions reach zero [1,2].

1.1 Literature Review

Many researchers have devised various LFC control algorithms to keep the frequency and tie-line power within acceptable limits during slow and moderate disturbances. Accurate mechanism-based power system models are required to produce higher solution quality with a high degree of precision and faster solution speed. There are various powerful intelligent controllers that have been developed for accurate modeling of controller gains, which is a challenging topic in modern power system networks. Elgerd OI et al. [3] have initiated the design idea about the area frequency response characteristics of each control area in interconnected power system. Another comprehensive study on automatic generation control (AGC) of power systems based on self-tuning control has been developed by Ibraheem et al [4]. Another classical control mechanism developed by KA Lee et al [5], called the stochastic AR-MAX model, has been introduced in the AGC problem. The present power system networks are more complex and highly non-linear due to high consumption of reactive power. The reactive power plays a major role in stabilizing the system frequency, which necessitated the requirement of intelligent control strategy. Many proficient control strategies have been employed to improve frequency stability of LFC. A Rubaai has focused on the intelligent self-tuning regulator in the field of load frequency control to measure the frequency error [6]. Another remarkable approach has been developed by CS Chang et al. for reducing steady state error by using a fuzzy gain scheduling approach [7]. The improvisation of frequency deviation using adaptive fuzzy gain scheduling was represented by E Cam et al [8]. Genetic algorithm (GA) optimization tools have been applied to parameter optimization of PID sliding mode controller in two control areas of interconnected power systems [9]. The optimum gain parameter of proportional integral control and minimization of the time dependent quadratic objective function of AGC using particle swarm optimization techniques [10]. E.Yesil et al. has developed self-tuning fuzzy PID controller for LFC studies [11]. A new control strategy of AGC is presented by T.P Imthias Ahamed using a reinforcement learning mechanism [12]. SR Khuntia et al have developed a combined approach using artificial neural network with a fuzzy inference system (ANFIS) in the area of LFC for obtaining the minimum dynamic response [13]. The hybrid combination of genetic algorithm and particle swarm optimization (HGAPSO) was developed by CF Juang et al. to minimize the area control errors of AGC [14]. SP Ghosal [15] began the sugeno fuzzy logic-based load frequency regulation of a multi-area power system. UK Rout et al. [16] proposed a differential evolution (DE)-based PI controller for AGC in linked power systems. optimal control model of Iranian power system with generator rate constant has been developed by KPS Parmar [17]. The artificial neural network (ANN) based automatic generation control has been developed by DK Chaturvedi et al [18]. LC Saikia has given an introductory concept using bacterial foraging (BF) technique to AGC in [19].

Many scholars have contributed ideas on typical controllers used in AGC, including as the Integral controller (I), Proportional Integral (PI), Proportional Integral and Derivative (PID), and Integral Double Derivative (IDD) [20]. Furthermore, the literature review reveals that AC tie lines are often used for multi-area connected systems, although HVDC connections for two regions receive the least attention. According to the printed works, many researchers have investigated thermal-hydro and thermal-thermal in AGC schemes, however the use of multi-area with AC-DC link for frequency stabilization is uncommon in practical power systems. DE optimized control in two area systems with HVDC link has been described by B. Mohanty et al. [21]. A. Barisal demonstrated teaching learning-based optimization (TLBO) for multi-source power-systems with HVDC connections that outperformed the DE optimized PID controller for the same power system [22].

S. Mirijalili created the whale optimization algorithm (WOA), a high-level mathematical optimization method. It is a population-based random search technique which is capable of dealing with multimodal objective functions as well as uni-fixed dimension objective functions. The authors have presented the WOA optimized PID controller in the multiple sources power system and a compare it with TLBO controller [22] and DE controller [21]. The fundamental benefit of the WOA approach over other well-known processes is that no specific parameters are required. It is simple and devoid of computational weight.

1.2 Motivation and Research Gap

According to prior research, the load frequency regulation of many sources of power system is viewed as a higher order transfer function model. To liberalize the higher order transfer function model and accurate controller setting, it requires strong, intelligent algorithms such as PSO, HGAPSO, DE, TLBO, ANFIS and ANN. These approaches have a longer time span to achieve frequency stability in multi-area power systems. The WOA is a population-based random search technique with better exploitation capability in the field of non-linear systems. Due to less convergence time, it is applied to optimal setting of controller gain in an AGC system. The major advantages of this approach are to avoid local minimums. The earlier optimization tools are not applicable to large scale systems. The WOA is ideally suited to liberalize the higher order transfer function model in order to provide precise frequency stability and superior dynamic performance of a specific power system.

1.3 Contribution of Present Work

- The proposed work's main contribution is to use the whale optimization method to determine the frequency response of single and multi-area power systems.
- The WOA algorithm tunes the PID controller gains, and the energetic performance of the proposed power system is assessed.
- This study's new approach is to compare a WOA regulated PID controller to a TLBO regulated PID controller, a DE regulated PID controller, and a robust optimum controller.
- The performance assessments of HVDC links and the frequency steadiness of systems by WOA optimized PID controller has been perfectly analyzed.
- The sensitive analysis, stability study and performance indices of AC-DC power systems have well demonstrated by suggested WOA-PID controllers.
- The robustness of the proposed technique has proven its computational stability by taking different loading patterns.

1.4 Highlights the Proposed Work

- The dynamic behaviour of the proposed work is computationally better than that of the DE-optimized controller in terms of settling time, damping ratio, and performance indicators.

- The purposeful work is more robust and computationally stable in comparison with the DE controller, TLBO controller, and optimal controller.

2. SYSTEM INVESTIGATION

The first step investigates a single area power system [20, 21]. This system is made up of three components: a hydro unit, a thermal unit, and a gas unit. For each unit of a single area system, proportional integral controllers are studied. Appendix I contains the nominal essential parameters of a single area system. The second scenario has two area systems with parallel AC-DC lines [21]. Each unit of the two area systems contains a PID controller. Each zone, according to the transfer function model, also contains a generator, turbine, and speed control mechanism. Appendix II contains all of the critical parameters of two area system. The many powers source output-input model of an AC-DC connection system is depicted in *figure 1*.

Because of its superior control capabilities and fast reaction, proportional integral derivative (PID) controllers are commonly used in modern power systems. The PID controller approach, as the name indicates, has three modes: proportional, integral, and derivative. Although the proportional controller has the ability to reduce rising time, it cannot completely remove steady state error. The integral controller has a poorer transient response, but the derivative controller reduces overshoots and improves stability. When stability and fast reaction are required, the PID controller comes in handy. In order to investigate higher dynamic performance, a WOA-optimized PID controller was used in this work. For the optimum controller design, four performance criteria are taken into account. Because they yield better findings than the integral absolute error (IAE) and integral square time error (ISTE), the integral time absolute error (ITAE) and integral square error (ISE) are often utilized in LFC investigations. In this work, ITAE is regarded as a higher objective function from an ideal stance. For low frequency inaccuracy, a proper range of controller gain settings is necessary. The purpose of adjusting the controller range is to decrease peak overshoot and settling time.

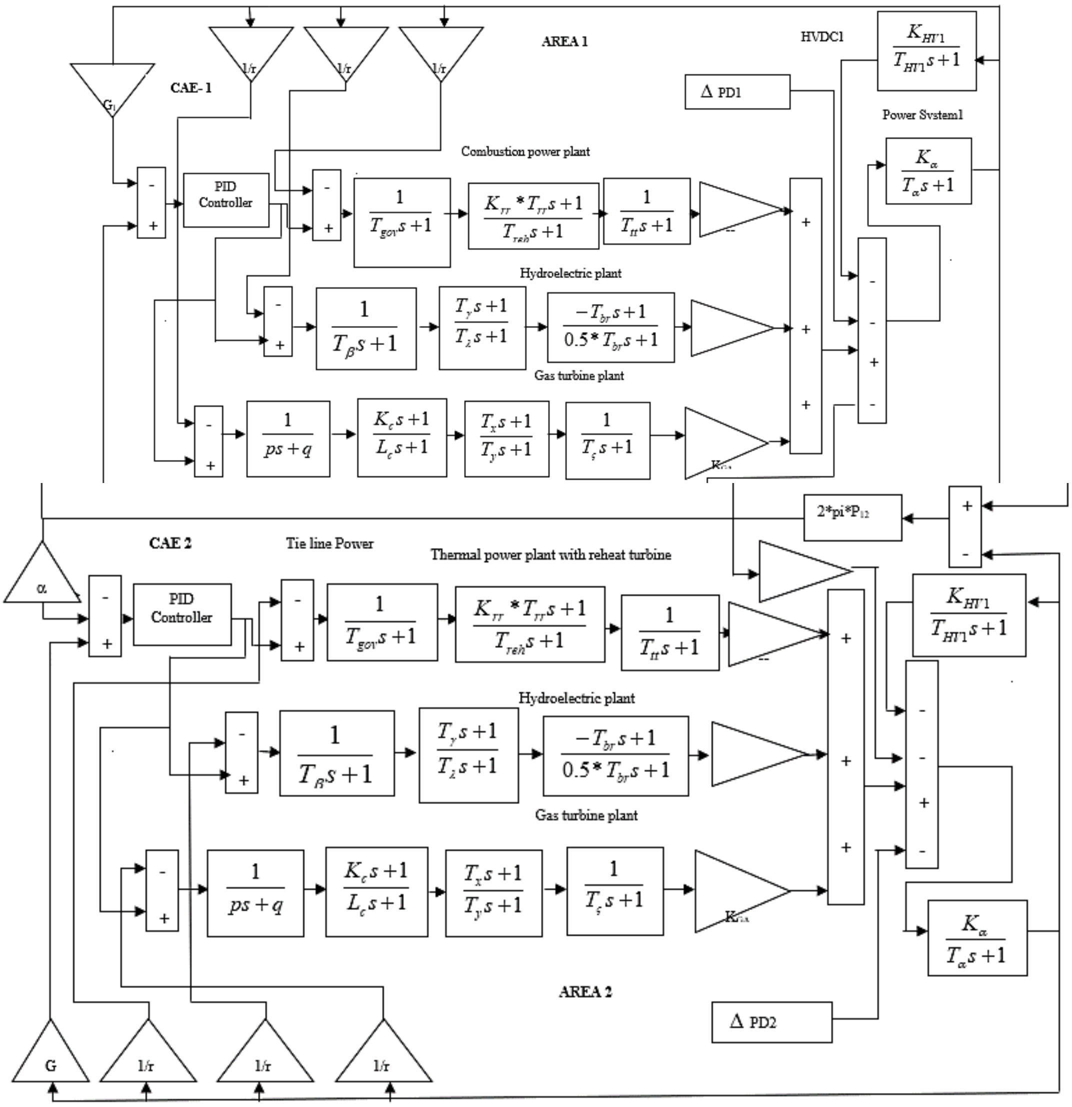

Figure 1: Multi-source AC-DC line transfer function model with PID controller

The suggested system's objective function is as follows:

$$P_{cos\,t} = ITAE = \int_0^{t_{simulation}} (|Del\ f_1| + |Del\ f_2| + |Del\ P_{Tie}|)\,.t.dt \qquad (1)$$

Where, $Del\ \Delta f_1$ represents frequency variations for area-1 and $Del\ \Delta f_2$ represents frequency variations for area-2. Similarly, $Del\ P_{Tie}$ represents tie line power change and $t_{simulation}$ indicates simulation time.

Minimize the objective function $P_{cos\,t}$ subject to:

$$G_{P\_\min} \le G_P \le G_{P\_\max}$$

Where G_{p-min} and G_{p-max} are the minimum and maximum controller gains. (2)

The PID controller equation of each production unit with respective control inputs CU_H, CU_G and CU_T are defined as:

$$CU_H = K_{P2}CAE_1 + K_{I2}\int CAE_1 + K_{D2}\frac{d(CAE_1)}{dt} \qquad (3)$$

$$CU_G = K_{P3}CAE_1 + K_{I3}\int CAE_1 + K_{D3}\frac{d(CAE_1)}{dt} \qquad (4)$$

$$CU_T = K_{P1}CAE_1 + K_{I1}\int CAE_1 + K_{D1}\frac{d(CAE_1)}{dt} \qquad (5)$$

Control area error (CAE) signal of two areas (area1 and area 2) can be written as follows:

$$CAE_1 = G_1\Delta f_1 + Del\ P_{Tie} \qquad (6)$$

$$CAE_2 = G_2\Delta f_2 - Del\ P_{Tie} \qquad (7)$$

WOA approach is used to allocate the optimal gains scheduling of PID controllers whose objective is to minimize the ITAE. Intelligent-based optimization algorithms are rapidly expanding due to ease implementation, shorter simulation time and improved performance [23].

3. WHALE OPTIMIZATION ALGORITHM

In 2016, S. Mirjalili et al. created the whale optimization algorithm (WOA), a revolutionary meta-heuristic technique [24]. The bubble-net hunting mechanism is used in this natural-inspired optimization strategy. Whales are said to be extremely intelligent animals. It is the world's biggest exotic animal. Humpback whales are well-known for their unusual hunting techniques. The bubble net feeding technique refers to whale foraging practices. In general, humpback whales like to eat on small fish near the surface of the ocean. WOA's mathematical model is divided into components such as surrounding prey, water cycle mechanism, and catching for fish.

3.1 Encircling Prey

Humpback whales locate prey and circle the area where they are praying. The best position in the search space was initially unknown. The WOA strategy to identifying the target prey is currently the best potential option in the first population phase. Following the identification of the best whales, the other agents develop their positions in relation to the top search agent. This section's mathematical expression is as follows:

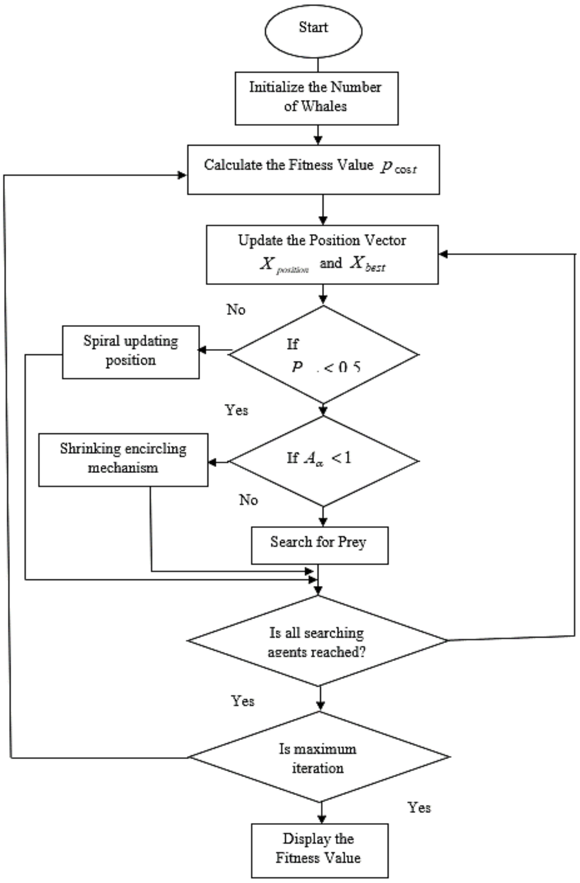

Figure 2: Flow chart for WOA Algorithm

$$D_{EP} = \left|C_X X_{best}(iter) - X_{position}(t)\right| \qquad (8)$$

$$X_{position}(iter+1) = X_{best}(t) - A_\alpha . D_{EP} \qquad (9)$$

$$A_\alpha = 2 \times a \times .rand - a \qquad (10)$$

$$C_X = 2 \times rand \qquad (11)$$

Where, $iter$ is the present iteration, A_α and C_X are constants, X_{best} gives best position among population, $X_{position}$ represents the position vectors. $rand$ is the random number.

3.2 Bubble-net Attacking Method

The bubble net attacking method's mathematical composition follows two rules:

1. Encircling Method: The value of A_α lies between -a to a a , when a decreases from 2 to 0 over iterations. By selecting A_α between -1 to 1, the update position of the search agent is defined as the difference between the initial position of agents and the best position of agents. In the population vector, it generates two-dimensional search spaces.
2. Upgradation of Spiral Path: This method calculates the path between the whale's location and the search location. To mimic the transition of cripple whales, an equation is established between the whale's location and the search position. The equation has written bellows.

$$X_{position}(t+1) = D_{EP}'.e^{bl}.cos(2\pi l) + X_{best}(iter) \quad (12)$$

D_{EP} = Best solution of ith whales, b = spiral constant, l = numbers between -1 to +1.

The probability for upgradation of cripple whales' position either the decreasing encircling methodology or the spiral model follows the circular path and a diminishing the circle at the same time.

Mathematically, a model can be described as:

$$X_{position}(iter+1) = \begin{Bmatrix} X_{best}(iter) - A_\alpha.D_{EP} if p_{mut} \leq 0.5 \\ D_{EP}'.e^{bl}.cos(2\pi l) + X_{best}(iter)\ if p_{mut} \geq 0.5 \end{Bmatrix} \quad (13)$$

3.3 Search for Prey (Exploration)

In this address, a variation of $A$is employed to search position. The search process of cripple is heuristically with respect to one other's positions. The movement of search agent is away from the reference position only when A >1 or A < -1. During the exploration phase, the search agent location is modified to reflect the heuristically picked search agent rather than the optimal search agent. When | A | > 1, the WOA technique exhibits exploration and it executes a global search. The model may be expressed mathematically as follows:

$$D_{EP} = |C_X.X_{rand} - X_{position}| \quad (14)$$

$$X_{position}(iter+1) = X_{rand} - A_\alpha.D_{EP} \quad (15)$$

4. EXECUTION OF WOA ALGORITHM TO LFC

The computational aspect of WOA for solving load frequency control is elaborated as follows. The computational modeling of WOA technique for LFC is shown in *figure 2*.

Step 1: Initialize the number of Whales (Initial population) between upper limit and lower limit of each variable $X_{position}(i = 1,2,3,\cdots N_p)$ where $N_p$the number of populations is *i.e.* number of Whales

Step2: Evaluate the fitness value of each whale. Calculate the performance index (ITAE) of each population.

Step 3: Update the position best search agent $X_{position}$ and X_{best}

Step4:

```
$while\ iter < \ iter\_max$
$for\ j = 1: N_p$
$for\ i = 1: number\ of\ \ var\,i\,ables$
$X_{position}(i,j) = X_{min\,imum} + rand(X_{max\,imum} - X_{min\,imum})$
$end$
$end$
```

Step 5: Choosing the suitable value of $a, A_\alpha, C_X, l\ and\ p_{mut}$ (Mutation process)

```
$if\ p_{mut} < 0.5$
$if\ A_\alpha < 1$
$Evaluate\ the\ position\ vector\ of\ whales$
$elseif\ A_\alpha > 1$
$select\ random\ position\ vector$
$Evaluate\ the\ position\ of\ search\ agent$
$end$
$eseif\ p_{mut} >\ 0.5$
$updating\ the\ position\ vector\ of\ search\ agent$
$end$
$end$
```

Step 6: Calculate the fitness evaluation (ITAE) from mutation

Step7: Update the position best search agent $X_{position}$ and X_{best}

$iter = iter_{max+1}$

end

Step8: print the value best position vector. The best position vector means the optimal controller gain calculation.

Step 9: plot the minimal value of ITAE

$iter = number\ of\ iteration;\ iter\_max = max\,i\,mum\ of\ iterations$

4.1 Elaborate the Optimization Process

i) Initially, a random population was generated between the lower and upper limits of the controller variable.
ii) Evaluate the fitness value of the objective function.
iii) Evaluate the position-best and global-best controller gains within the population.
iv) By choosing a suitable value, $a, A_\alpha, C_X, landp_{mut}$ the next step is the mutation process.
v) If P_{mut} is less than 0.5 and A_α is less than 1, the process of generating new offspring (Whales)
vi) Then, again, evaluate the objective function. In the objective function, the best agent is evaluated.
vii) There is a crossover mechanism for the survival of the best agent.
viii) Then the computation iteration stops.

The choice of choosing the objective function is to reduce static frequency error to a minimal value and allocate optimal controller gain for interconnected power system.

5. SIMULATION RESULTS AND DISCUSSION

This research work is carried out on the MATLAB R2021a environment on i7 processor, 1.80GHz and 8.00 GB RAM PC. The LFC model has drawn on the MATLAB/SIMULINK environment and the WOA program has written in MATLAB editor prompt to obtain optimal values of controller gain. The perfect command is given to link the editor command with the SIMULINK prompt to minimize the objective function. Here, the change in demand is considered a 1% load perturbation in area 1. The range of control gain is chosen -1 to 1. The system parameters have been taken from Appendices I and II for the simulation of a particular power system. The controller gain has been optimized by the MATLAB m. file and linked to the SIMULINK model by the command **“load_sytem(.mdl) and sim(.mdl)”.** The simulation time taken for cases I and II is 50 seconds. The step load has been taken for the simulation study.

5.1 Case I: Single area multi source power system

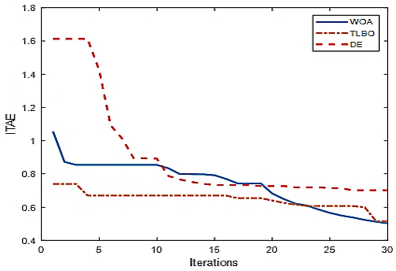

Figure 3: Convergence graph of ITAE for single area system with Integral Controller (case I)

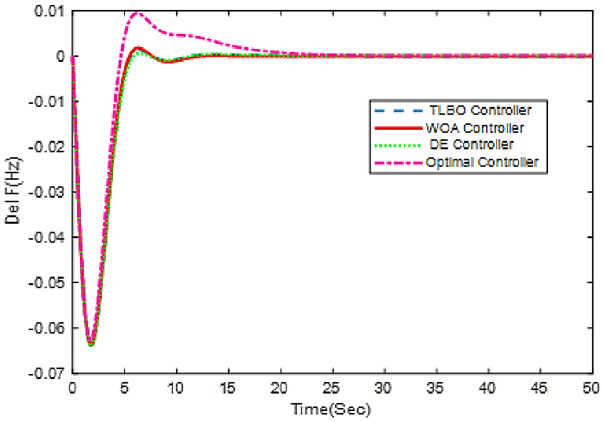

Figure 4: Frequency deviation of single area system (Case I)

Table 1: Controller parameters for Case I

Methods		**WOA Controller**	**TLBO [22]**	**DE [21]**	**Optimal Controller [20]**
Integral Controller	K_{I1}	0.0445	0.0511	0.0516	0.1514
	K_{I2}	0.0076	0.0041	0.0071	0.0131
	K_{I3}	0.211	0.1847	0.1701	0.0708
System Modes		-19.9861 + 0.0000i	-19.9732 + 0.0000i	-19.9860 + 0.0000i	-19.9859 + 0.0000i
		-12.6457 + 0.0000i	-12.5516 + 0.0000i	-12.6456 + 0.0000i	-12.6429 + 0.0000i
		-5.8194 + 0.0000i	-6.7664 + 0.0000i	-5.8243 + 0.0000i	-5.8415 + 0.0000i
		-5.0000 + 0.0000i	-4.2343 + 1.1472i	-5.0000 + 0.0000i	-5.0000 + 0.0000i
		-4.0000 + 0.0000i	-4.2343 - 1.1472i	-3.9946 + 0.0000i	-3.9735 + 0.0000i
		-2.9879 + 0.0000i	-2.6617 + 0.0000i	-2.9878 + 0.0000i	-3.0062 + 0.0000i
		-0.5184 + 0.8549i	-1.2895 + 0.0000i	-0.5377 + 0.8609i	-0.5103 + 0.8810i
		-0.5184 - 0.8549i	-0.5274 + 0.8598i	-0.5377 - 0.8609i	-0.5103 - 0.8810i
		-1.2677 + 0.0000i	-0.5274 – 0.8598i	-1.2787 + 0.0000i	-1.3331 + 0.0000i
		-0.5233 + 0.0000i	-0.4923 + 0.0000i	-0.4671 + 0.0000i	-0.2824 + 0.0777i
		-0.1026 + 0.0000i	-0.1091 + 0.0000i	-0.1101 + 0.0000i	-0.2824 - 0.0777i
		-0.0335 + 0.0000i	-0.0328 + 0.0000i	-0.0334 + 0.0000i	-0.0347 + 0.0000i
		0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0000 + 0.0000i	-0.0000 + 0.0000i
		-0.0000 + 0.0000i	-0.0000 + 0.0000i	-0.0000 - 0.0000i	-0.0000 - 0.0000i
		0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
Damping Ratio		**0.538**	0.5229	0.0301	0.5012
ITAE		**0.5044**	0.5135	0.5165	0.9934
Settling Time (Secs)		**4.98**	5.23	5.41	15.75

Table 2: Damping ratio calculation of Case I

Pole/Zero location	**Damping ratio**	**Frequency (rad/seconds)**	**Time Constant (Seconds)**
2.30e-17	-1.00e+00	2.30e-17	-4.34e+16
-5.52e-16	1.00e+00	5.52e-16	1.81e+15
-3.35e-02	1.00e+00	3.35e-02	2.99e+01
-1.03e-01	1.00e+00	1.03e-01	9.75e+00
-5.23e-01	1.00e+00	5.23e-01	1.91e+00
-5.18e-01 + 8.55e-01i	**5.18e-01**	**1.00e+00**	**1.93e+00**
-5.18e-01 - 8.55e-01i	5.18e-01	1.00e+00	1.93e+00
-1.26e+00	1.00e+00	1.26e+00	7.96e-01
-3.41e+00 + 2.55e-01i	9.97e-01	3.42e+00	2.93e-01
-3.41e+00 - 2.55e-01i	9.97e-01	3.42e+00	2.93e-01
-4.88e+00	1.00e+00	4.88e+00	2.05e-01
-6.18e+00	1.00e+00	6.18e+00	1.62e-01
-1.26e+01	1.00e+00	1.26e+01	7.94e-02
-2.00e+01	1.00e+00	2.00e+01	5.01e-02

In this study, a proportional integral based on a single area multi-source power system was taken for frequency stabilization. The proportional integral controller gains are suitable designed by WOA algorithm which reduces the objective function in a shorter simulation time. *Figure 3* shows the converged characteristics of ITAE with iterations. From this convergence graph, it shows that the WOA optimized ITAE gives better computational stability in comparison with DE optimized ITAE [21] and TLBO optimized ITAE [22]. The lower number of iterations is obtained by the WOA algorithm, which is a prime indicator of computational convergence. The damping ratio is another aspect of choosing frequency stability. Here, the damping ratio is 0.518 and is less in comparison with the existing DE optimized controller and TLBO optimized controller. The suggested technique has a settling time of 4.98 seconds, which is smaller than the TLBO (5.23 seconds), DE (5.41 seconds), and optimal control (15.75 seconds). *Table 2* shows the damping ratio and time constant of the WOA optimized control. *Figure 4* depicts the frequency response of single area system with 1% step load perturbation. From frequency response plot, the DE optimized controller takes more overshoot time, while WOA based PI controller takes less overshoot. As can be seen from the above explanation, the WOA optimized PID controller gives significant results in comparison with reported controllers in terms of system responsiveness.

5.2 Case II: Two area interconnected power system

Two locations with combustion, hydroelectric, and gas-generating plants with AC-DC connections were analyzed in this scenario. This study is separated into two control zones, each having three PID controllers used to demonstrate LFC stability. In area-1, a 1% step load pattern is used. The best PID controller gains with AC and AC-DC parallel lines are shown in *table 3*. WOA optimized PID controllers' optimum gains were compared to those of published techniques TLBO [22] and DE [21] optimized PID controllers. The best performance of different objective functions and settling time of 2%-time band is shown in *table 4*. *Table 4* summarizes the performance analysis of frequency deviation in terms of ITAE, ITSE, ISE and IAE, and WOA optimized PID controller settings. The settling time for the ITAE objective function is 2.21 seconds, which is less than the values obtained TLBO optimized controller [22], DE optimized PID controller [21] and optimal controller [20]. *Figure 5* gives the convergence characteristics of ITAE with 30 numbers of iterations. The WOA based optimization gives better computational convergence in comparison with DE, TLBO and optimal control. To evaluate the advantages of the WOA technique, the energetic presentation of an AC tie line for a 1% step load change are shown in *figure 6-8*. As demonstrated in *figures 6-8*, WOA optimized controllers are more comparable to the damping response of the AC tie line in terms of settling time, tie line power variations, and frequency overshoot and undershoot. *Figure 9* shows the convergence characteristic of ITAE of AC_DC lines. *Figure 10* to *12* exhibit the dynamic responses of an AC-DC line in terms of settling time, tie-line power fluctuations, undershoot and overshoot frequency deviations, and area control error. In terms of dynamic performance, the data shows that the WOA optimized controller surpasses the TLBO and DE optimized controllers.

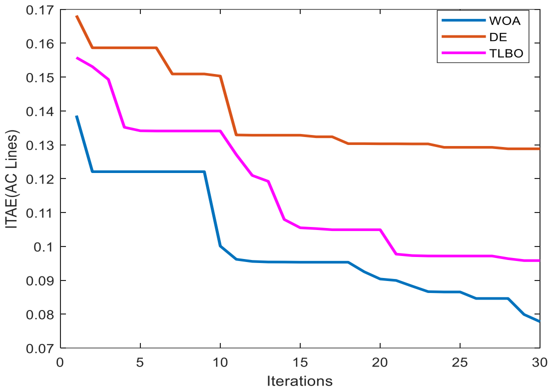

Figure 5: Convergence character of ITAE with AC line for Case II

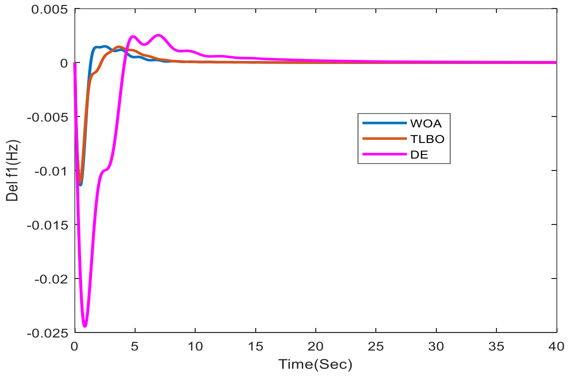

Figure 6: Frequency deviation of area-1 (AC lines)

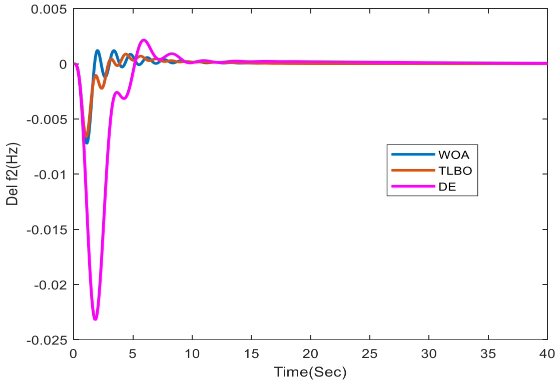

Figure 7: Frequency deviation of area-2 (AC lines)

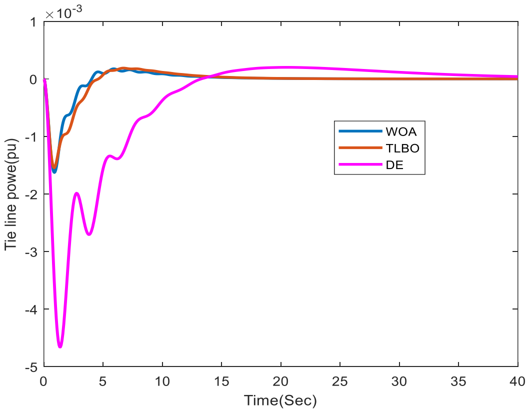

Figure 8: Tie line power deviation (AC lines)

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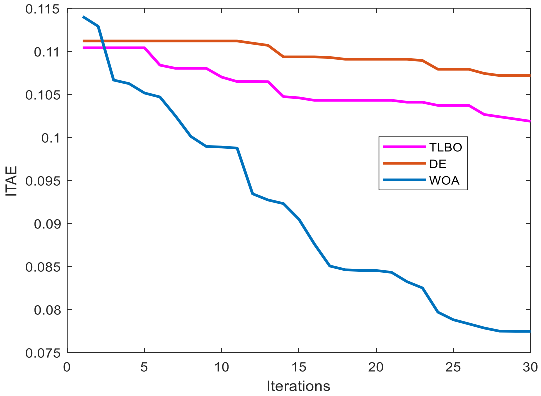

Figure 9: Convergence character of ITAE with AC-DC line (Case II)

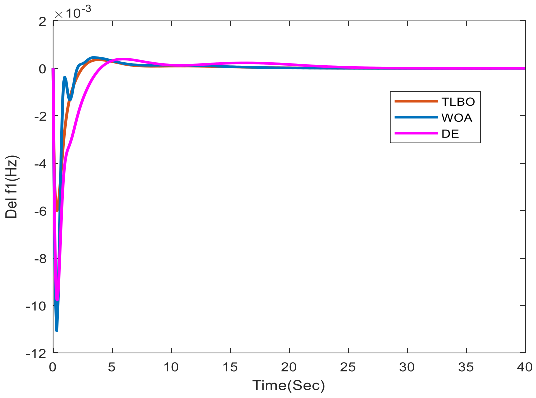

Figure 10: Frequency deviation of area-1 (AC-DC lines)

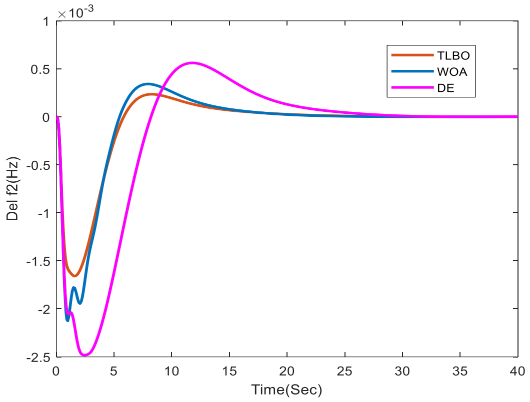

Figure 11: Frequency deviation of area-2 (AC-DC lines)

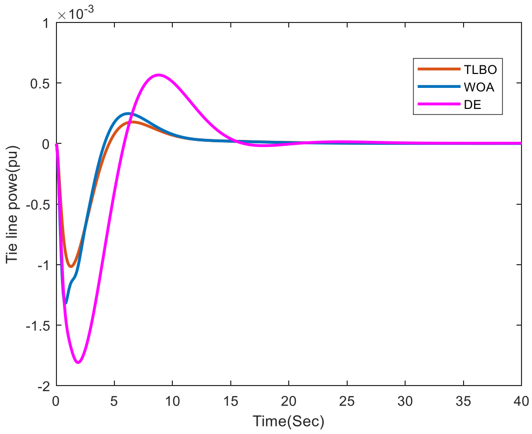

Figure 12: Tie line power deviation (AC-DC lines)

Table 3: WOA optimized PID controller gains for AC line and AC-DC lines

Structure of power system	WOA optimized PID controller gains		
	Thermal Plant	**Hydro Plant**	**Gas-Turbine Plant**
Power system with AC line	K_p=4.3993 K_i=4.9405 K_D=2.882	K_p=4.1604 K_i=1.3167 K_D=2.3877	K_p=4.1877 K_i=4.2619 K_D=3.3041
Power system with DC line	K_p=3.8847 K_i=4.4070 K_D=0.0000	K_p=5.0000 K_i=0.0001 K_D=0.0000	K_p=2.3657 K_i=4.7806 K_D=0.3488

Table 4: Performance Indices of multi-source power system with AC-DC lines

Performance Indices	Power system with AC line			
	WOA Controller	**TLBO Controller [22]**	**DE Controller [21]**	**Optimal Controller [20]**
ITAE	**0.0778**	30.1024×10^{-04}	44.7442×10^{-04}	15.445×10^{-3}
ISE	**0.0001192**	11.1210×10^{-2}	52.551×10^{-2}	1.7372
ITSE	**0.0001031**	15.4289×10^{-4}	28.23×10^{-4}	55.742×10^{-4}
IAE	**0.02791**	11.3410×10^{-2}	11.7244×10^{-2}	24.475×10^{-2}
Settling Time (Secs)	**Δf_1=2.21** **Δf_2=1.98** **ΔP_{Tie}=0** **ACE_1=1.92** **ACE_2=0**	Δf_1=2.28 Δf_2=2.88 ΔP_{Tie}=0 ACE_1=2.3 ACE_2=0	Δf_1=3.77 Δf_2=4.58 ΔP_{Tie}=4.29 ACE_1=4.19 ACE_2=2.64	Δf_1=11.86 Δf_2=14.47 ΔP_{Tie}=6.71 ACE_1=9.34 ACE_2=19.77
Power system with AC-DC line				
ITAE	**0.0774**	0.10296	0.1987	1.9037
ISE	**$6.068e^{-05}$**	3.4388×10^{-05}	19.22×10^{-05}	9.49×10^{-4}
ITSE	**$4.896e^{-05}$**	2.197295×10^{-05}	34.79×10^{-05}	52.74×10^{-4}
IAE	**0.02166**	0.01854	0.04212	0.1381
Settling Time (Secs)	**Δf_1=1.2** **Δf_2=0** **ΔP_{Tie}=0**	Δf_1=1.48 Δf_2=0 ΔP_{Tie}=0	Δf_1=23.31 Δf_2=4.13 ΔP_{Tie}=3.81	Δf_1=4.56 Δf_2=5.61 ΔP_{Tie}=11.36

5.3 Chosen parameters of WOA for different cases

The right configuration of the WOA algorithm is critical for various case studies in LFC. The values a and C_X must be modified during the optimization process. The purposed algorithm's exploitation and exploration capacity was obtained by reducing the value of a during iteration. The coefficient vector A_α has changed as the value a has been modified. During the iteration time, the variable a must be adjusted from 2 to 0. The best-chosen value of a is 1.5. The A_α is the decision variable for allocating the optimal position vector between the current and prey positions. The optimal rang of A_α lies between -1 to 1. The population size chosen for different case studies is 20. The number of Whales chosen is 20, coefficient vector A_α is 0.2, $C_X$is 1.2 for case I and for case II, number of Whales is 20, A_α is 0.4, $C_X$is 1.5.

5.4 Computational Stability

Previously, the ITAE objective function was used in the simulation study for LFC. In order to improve the robustness of the particular power system, all cost functions have been taken, i.e., ITAE, ISE, ITSE, and IAE. The performance analysis of PID controller gain and optimal values of the cost function are shown in *tables 3* and *4*. From *table 4*, it is concluded that the ITAE value is **0.0778,** which is less in comparison with the TLBO controller, and the settling time is 2.21, and the percentage increase in the settling time is 30% in the power system with the AC line. Similarly for the AC-DC parallel line. The ITAE value of 0.0774 for the WOA optimized controller is very low in comparison with the TLBO controller, DE optimized controller, and optimal controller. The better frequency deviation obtained by choosing the cost function is ITSE, and the maximum overshoot is obtained by ISE. It has been determined that analysing the maximum overshoot is preferable to settling time. So, ISE is the better objective function for choosing both reducing settling time and overshooting. By choosing the best cost function, the robustness of the power system is rapidly enhanced. The convergence characteristics of ITAE take 30 iterations to reach the optimal value using the WOA method. From *figure 9*, the convergence characteristics of ITAE are the optimal value with a faster convergence rate in comparison with the TLBO and DE methods. From the analysis, the WOA-based technique gives less computational time with a minimum iteration, which leads to better computational stability.

6. CONCLUSION

The Whale Optimization Algorithm (WOA) is employed to minimize the different objective functions and better modeling of PID controller gains. This research also considers AC tie lines and AC-DC linkages for two linked sectors. The integral time absolute error (ITAE) cost function was used to optimize the system's responsiveness in terms of overshoots and settling time. In terms of damping performance for frequency change, tie line power variation, and overall power system resilience, the WOA optimized PID controller outperforms the TLBO and DE optimized PID controllers. Furthermore, the sizes of the SLP, system parameters, and variations in loading conditions have no impact on this WOA system. The computational architecture of the WOA algorithm is best suited for real time application when penetrating renewable energy sources like wind turbines and PV cells. In real-time applications, this particular power system model can be tested with random load changes, industrial loads, and residential loads, which leads to the practicability of the system. For better frequency stability, the author suggested using the virtual inertia control loop for better frequency stability with fuzzy-based optimization techniques and also including a damping factor in the virtual inertia control loop.

Appendix I: Single area system (Case I)

G_1= 0.4312 p.u MW/Hz; P_{rated} = 2000MW/Hz ;P_{Loss} = 1840MW; re1 = re2 = re3 = 2.4 Hz/pu; T_{gov} = 0.08 s;T_{th} = 0.3 s; K_{rr} = 0.3; T_{reh} = 10 s; K_{TH} = 0.543478; K_{HY} = 0.326084; K_{GA} = 0.130438; T_β = 0.2 s; T_λ = 28.75 s; T_γ = 5 s; T_{br} = 1 s; p = 0.05 s; q = 1; K_c = 0.6 s; L_c = 1 s; T_x = 0.01 s; T_y = 0.23s; T_γ = 0.2 s; T_α = 11.49 s; K_α = 68.9566 Hz/pu;;P_{12} = 0.0433 pu; $\alpha_{12} = -1$.

Appendix II: AC-DC system (Case II)

f = 60 Hz; G_1 = G_2 = 0.4312 p.u. MW/Hz; P_{rated} = 2000MW (rating), P_{Loss} = 1840MW (nominal loading); re1 = re2 = re3 = 2.4 Hz/pu MW; T_{gov} = 0.08 s; T_{reh} = 10 s; K_{rr} = 0.3; T_{rr} = 0.3 s; K_{TH} = 0.543478; K_{HY} = 0.326084; K_{GA} = 0.130438; T_β = 0.2 s; T_γ = 28.75 s; T_λ = 5 s; T_{br} = 1 s; p = 0.05 s; q= 1; K_c = 0.6 s; L_c = 1 s; T_x = 0.01 s; T_y = 0.23s; T_γ = 0.2 s; $T_{\alpha1}$ = $T_{\alpha2}$= 11.49 s; $K_{\alpha1}$ = $K_{\alpha2}$ = 68.9566 Hz/pu MW; T_{HV} = 0.2 s; K_{HV} = 1;P_{12} = 0.0433 pu, $\alpha_{12} = -1$

List of Abbreviations

G_1, G_2= Bias frequency; CAE_1, CAE_2 = Control area errors; re1,re2,re3= Speed regulations (p.u); T_{gov1} , T_{gov2} = Time constant of governor (sec); ΔP_{G1}, ΔP_{G2}= Output command of governor (p.u); T_{th1} ,T_{th2} = Time constant of turbine (sec) ;ΔP_{T1},ΔP_{T2} = Output power of turbine ;$\Delta PD1$, $\Delta PD2$ =change in load; $Del\ P_{Tie}$ = Variations of tie line powers (p.u); $K_{\alpha1}$, $K_{\alpha2}$= Power system gains; $T_{\alpha1}$, $T_{\alpha2}$=Time constant of the power system(Sec);$del\ f_1$, $del\ f_2$ =Frequency change (Hz); P_{12} =Synchronization coefficient.

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