Stability Enhancement of Single Machine Infinite Bus System with UPFC using Bat Algorithm

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***Abstract*—A major challenge in highly interconnected power systems is ensuring the stability of their networks. Even though low-frequency oscillations may not appear to be too harmful at first glance, the failure to dampen out the oscillatory signals can result in the system losing synchronization. Flexible AC Transmission Systems (FACTS) devices are effective in suppressing oscillations as well as enhancing power transfer rates. Among many devices within FACTS, the Unified Power Flow Controller (UPFC) is one of the most sophisticated and effective power flow controllers available. UPFC parameter optimization concerns real-time power systems problem with multiple objectives. In this paper, the optimization of UPFC parameters is carried out using a novel optimization approach named Bat Algorithm (BA) to dampen out the small signal oscillations, and thereby enhancing the stability of the system. The time domain simulation results of the proposed BA-tuned UPFC are compared with the results of a Tunicate Swarm Algorithm (TSA) tuned UPFC and also with a conventional fixed gain UPFC to measure the efficacy of the proposed algorithm. Also, a comparison is made between the eigenvalues of both the optimized and conventional UPFCs. Both the eigenvalue analysis as well as the time domain representation of system parameters ensures the superiority of the suggested controller over the traditional controller in all aspect.**

I. Introduction

A lot of network systems have been made by human beings throughout the span of science and technology. Power system networks are among the most complex and largest among them. Power system networks experience various types of disturbances all of the times which causes low frequency oscillations in the system. The power network becomes unstable due to these low-frequency oscillations. To damp out these oscillations as well as to control the flow of power through a line, FACTS devices are used rather than using constant voltage devices. A number of FACTS controllers are available now-a-days but among them series controller can control power and current flows through a line more effectively by damping out the oscillations. UPFCs are series shunt controllers in which all three of the parameters (voltage, impedance, and angle) are controlled simultaneously to control the flow of power through transmission lines, and also to determine whether it is too much or too little [1]. It's one of the most important and most effective FACTS devices installed in AC transmission systems by which both the active power and reactive power flow in the transmission line can be controlled. To improve the damping of oscillations in a Single Machine Infinite Bus (SMIB) system, UPFC devices are used, and different optimization techniques are adopted to optimize the parameters of UPFC.

Engineers are frequently tasked with creating and operating systems that achieve or surpass predetermined objectives while conforming to a number of design and operational constraints. The coordination of the quest for suitable designs and techniques of operation is known as optimization. It specifies the set of activities or items that must be implemented in order to obtain optimal system performance. Optimization, in its most basic form, finds the optimal or least value of an objective function for variables defined within a viable range. In a broader sense, optimization is the process of searching for a set of variables that produces the optimal values for single or multiple objective functions while fulfilling a variety of constraints.

Optimization has become one of the most important mathematical techniques because of its frequent and fundamental applications in most engineering activities. To achieve success in any field, continuous improvement is a must. The performance of any system can be improved by having a thorough understanding of all factors that affect it. By improving system's performance, the best results out of available resources can be obtained. An optimization technique attempts to identify the most efficient solution out of all the possible ones and makes the best judgments within a set of constraints.

Optimization can be used to solve or improve a variety of problems and practical applications in a variety of industries. Linear programming (LP), Mixed-integer programming (MIP), Stochastic programming (SLP), Decomposition methods and Artificial intelligence methods (AI) are the most common optimization techniques. Artificial intelligence methods of optimization have caught people's attention in recent times. Algorithms used in the AI method of optimization can be separated into two groups: Heuristics and Metaheuristics. Heuristic algorithms are highly specialized and specific to a certain task. On the other hand, metaheuristic algorithm refers to a self-dependent, high-level algorithm. Heuristic optimization algorithms are measurable through a bunch of suggestions or approaches dependent on a metaheuristic algorithm.

In the recent two decades, the field of metaheuristic algorithms has grown considerably [2]. Metaheuristic algorithms have demonstrated promising results in tackling most real-world optimization issues in the recent years. In a

SMIB system, UPFC parameters can be optimized using many well-known metaheuristic algorithms such as, Genetic Algorithm (GA) [3], Simulated Annealing (SA) [4], Tabu Search (TS) [5], Particle Swarm Optimization (PSO) [6], Cat Swarm Optimization (CSO) [7], Cuckoo Search (CS) [8], Gravitational Search Algorithm (GSA) [9], Ant Colony Optimization (ACO) [10], Ant Lion Optimizer (ALO) [11], Multi-Verse Optimizer (MVO) [12], Sine Cosine Algorithm (SCA) [13], Grasshopper Optimization Algorithm (GOA) [14], Salp Swarm Algorithm (SSA) [15], Harris Hawks Optimization (HHO) [16]. These are the metaheuristic algorithms inspired by nature. All these algorithms can be divided into four types. Fig. 1 and Fig. 2 depict the categorization of nature-based metaheuristic algorithms.

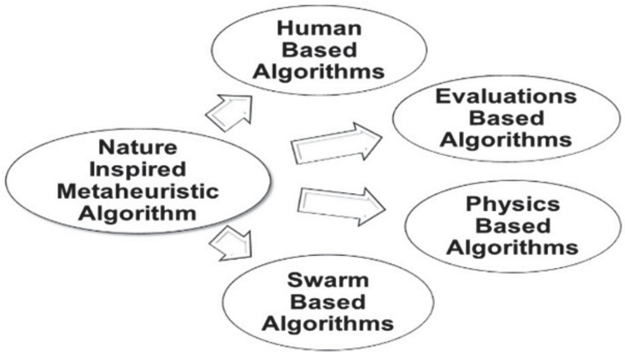

Fig. 1. Nature Inspired Metaheuristic Algorithms

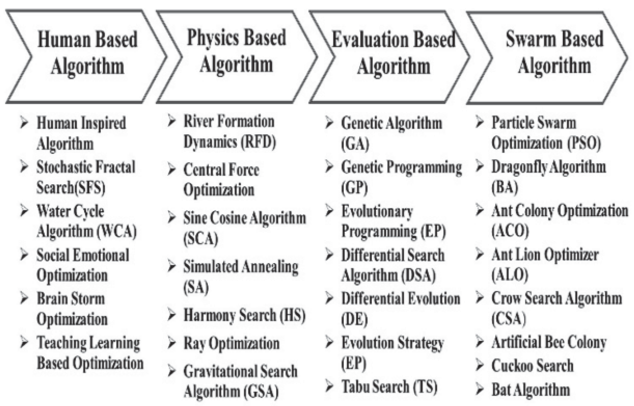

Fig. 2. Metaheuristic Algorithms of Various Types

Bat Algorithm is a newly introduced metaheuristic algorithm introduced by Xin-She Yang in 2010 [17]. It's a Swarm-Based algorithm which has attracted considerable attention in the last several years. This algorithm was motivated by the echo-locative nature of microbats. Microbats have an unusual echolocation capacity, since they can detect their prey and distinguish between various species of arthropods even in full eclipse. Bats move around the environment and collect food from different sources. In the case of optimization process, the bats are the search agents, the environment is the search area, each point within the environment is a possible solution, the quality of the prey represents the objective function, and the best prey located within the environment is the ideal solution for the problem. These commonalities enable this method in solving optimization issues through simulating the echo-locative nature of bats.

BA is very simple with some adjustable parameters (Frequency, Position, Velocity, Loudness, Pulse Rate) that makes it highly appealing for application in several technical fields. BA is easier to implement comparing to other algorithms like GA, PSO, HS etc. It's a highly efficient and time-saving technique with the purpose of determining the best solution in a large search area. The value of BA is assessed by addressing several engineering design problems with various types of objective functions, constraints, and decision factors. Considering the BA's efficacy in improving the stability of a power system with other FACTS devices, the effectiveness of the BA should be carried out for the stability enhancement in a SMIB-UPFC system. As far as the author's best of knowledge, such kind of study has not been conducted yet.

In this paper, Bat Algorithm (BA) is used to tune the parameters of UPFC of a SMIB system for damping out the oscillations, and to analyze performance of the system.

II. POWER SYSTEM MODELING

A. Single Machine Infinite Bus

A single machine attached with an infinite bus is shown in Fig. 3. It is a simplified power system model in which an infinite bus of a voltage source with fixed frequency and voltage is assumed. In this type of system, the amplitude of infinite bus voltage (V_e) will be constant when the machine is subjected to any perturbances that causes the system to be unstable. The changes of amplitude of V_e, indicates a changed operating condition of external network whenever the steady state condition of the system alters. The SMIB system is a multi-variable nonlinear time variant system, defined by known set of equations. A simplified linearized model is considered for analyzing and designing of the control system of a synchronous generator for application purposes.

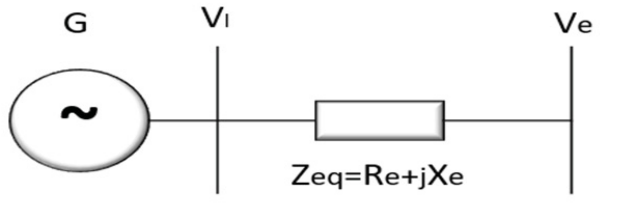

Fig. 3. Line Diagram of Single Machine Infinite Bus

B. Unified Power Flow Controller (UPFC)

The UPFC is a hybrid of two compensator named static synchronous compensator (STATCOM) and static synchronous series compensator (SSSC), connected by a shared DC voltage link [18]. It is a type of series-shunt controller that can regulate active (real) and reactive (imaginary) power through a transmission line while managing the voltage at the AC bus. The magnitude and phase angle of the voltage may be adjusted separately. It is a quick-acting device with outstanding performance and adaptability that adds additional control capabilities to the transmission systems. UPFC can regulate impedance, voltage, and angle of the transmission line as well as the power flow (both real and reactive) in the line simultaneously or selectively by utilizing angularly unconstrained series voltage injection [19][20]. In addition, the UPFC may enable independently controlled shunt reactive compensation. Fig. 4 depicts the circuit diagram of an UPFC. The gain, K, and time constants T1, T2, T3, T4 of the UPFC have a direct impact on the system's stability. Therefore, optimizing these parameters is required to increase the system's stability.

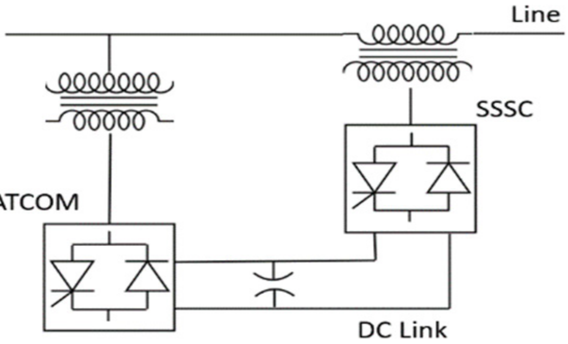

Fig. 4. Unified Power Flow Controller.

C. Single Machine Infinite Bus with UPFC

In a SMIB system, the synchronous machine works as the main part for the power system [21]. In this sort of system, the synchronous machine is attached to an infinite bus via a transmission line. Fig. 5 depicts a single-line schematic of a UPFC equipped SMIB system.

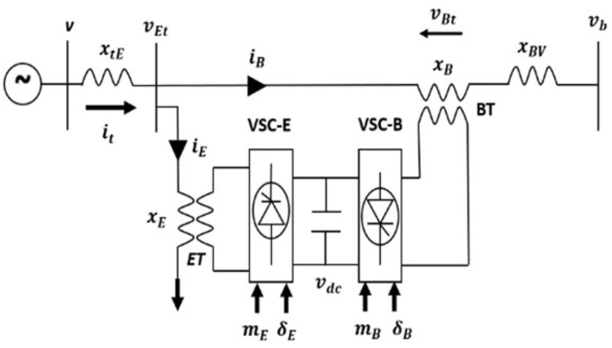

Fig. 5. UPFC equiped SMIB System

As seen from the above figure, a transmission line links the source end to an infinite bus via two transformers, the excitation transformer (ET), and the boosting transformer (BT). By the way of the transmission line, these transformers link the UPFC to the electric grid. The UPFC's primary structural elements are the two three-phase voltage source converters, VSC-B and VSC-E are coupled by an identical DC link capacitor. The UPFC is controlled by four signals. These are the ratio of amplitude modulation for boosting transformer, and excitation transformer (m_B and m_E), and phase angle for boosting transformer and excitation transformer (δ_B and δ_E).

The following three equations (1-3) represent the SMIB system's nonlinear model as illustrated in Fig. 5 [22]:

$$\dot{\delta} = \omega_b(\omega - 1) \quad (1)$$

$$\dot{\omega} = \frac{1}{2H}[P_m - D(\omega - 1) - P_e] \quad (2)$$

$$\ddot{E}_q = \frac{1}{\dot{T}_{do}}\left[E_{fd} - (x_d - \dot{x}_d)i_d - \dot{E}_q\right] \quad (3)$$

In these equations, P_m, P_e, D, and H denote the input mechanical power, output electrical power, damping coefficient, and inertia constant respectively; ω_b is the synchronous speed, ω represents the generator's rotating speed, and δ is the rotor angle; the field and generator internal voltages are denoted by E_{fd} and $\dot{E}_q$ respectively; x_d and $\dot{x}_d$ indicate the synchronous machine's transient and sub-transient reactance along the direct axis respectively. $\dot{T}_{do}$ denotes the open circuit field time constant. The generator armature current's direct axis component is denoted by i_d.

The reactive power (P_e) and terminal voltage (v_t) can be depicted by using the quadrature and direct axes of currents and voltages as follows:

$$P_e = v_d i_d + v_q i_q \quad (4)$$

$$v_t = \sqrt{\left(v_d^2 + v_q^2\right)} \quad (5)$$

The generator terminal voltage's (v_t) direct axis component is denoted by v_d whereas the quadrature axis component is denoted by v_q. Similarly, the generator armature current's direct and quadrature axis components are denoted by i_d and i_q. The v_d and v_q voltages can be expressed as follows:

$$v_d = x_q i_q = x_q\left(i_{iq} + i_{lq}\right) \quad (6)$$

$$v_q = \dot{E}_q - \dot{x}_d i_d \quad (7)$$

$$i_q = i_{Eq} + i_{Bq} \quad (8)$$

$$i_d = i_{Ed} + i_{Bd} \quad (9)$$

Here, x_q denotes synchronous reactance of the quadrature axis, and i_B and i_E denote the series transformer's currents and shunt transformer's current respectively. The symbols i_{Bd}, i_{Bq}, i_{Ed} and i_{Eq} indicate the division of i_B and i_E into quadrature and direct axis components.

III. Proposed Problem for Optimization

A multi-objective function based on Eigenvalues has been adopted for the optimization issue, which combines two important decision-making parameters which are damping ratio and damping factor. The primary objective function is J which is the combination of two distinct functions, J_1 *and* J_2, as shown below [23]:

$$J = (J_1 + \alpha J_2) \quad (10)$$

$$J = \sum_{\sigma_p \geq \sigma_0}\left(\sigma_o - \sigma_p\right)^2 + \alpha \sum_{\zeta_p \geq \zeta_o}\left(\zeta_o \geq \zeta_p\right)^2 \quad (11)$$

Here, p and o denote the system's Eigenvalue index and operating conditions index respectively. The system's relative stability is defined by the real part of Eigenvalue that is indicated by σ_p. ζ_p indicates the p-th Eigenvalue's damping ratio. The weighting factor 'α' combines σ_p and ζ_p, and in this paper, it has been set to 10. In the optimization process, the value of σ_o represents the relative stability of the damping factor margin that is provided to constrain the placement of eigenvalues.

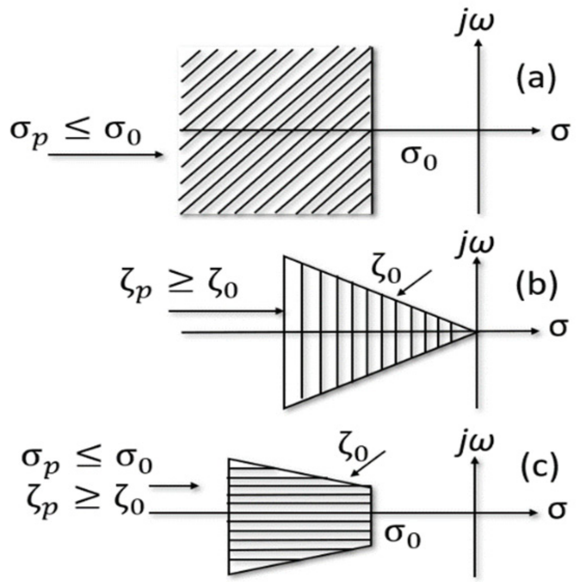

Fig. 6. Region of eigenvalue location for objective functions

Fig. 6 illustrates a graphical depiction of the chosen objective functions in the area of the stability of the system. When J_1 is selected as the objective function, the closed loop eigenvalues are presented at the left edge of the dotted line in Fig. 6a. Similarly, if J_2 is taken into account, it restricts the maximum overshoot of the eigenvalues, as shown in Fig. 6b. For J_2, ζ_0 denotes the lowest damping ratio that should be obtained. The eigenvalues in the case of optimization with J are confined to an area of shape-D, as seen in Fig. 6c.

Minimize J

Subjected to

$$K^{min} \leq K \leq K^{max}$$

$${T_1}^{min} \leq T_1 \leq {T_1}^{max}$$

$${T_2}^{min} \leq T_2 \leq {T_2}^{max}$$

$${T_3}^{min} \leq T_3 \leq {T_3}^{max}$$

$${T_4}^{min} \leq T_4 \leq {T_4}^{max}$$

The gain, K of the controller, and time constants, T_1, T_2, T_3, T_4 influence the stability of a power system. That's why optimization of these parameters is necessary, and this requirement can be fulfilled by the objective function (J). Therefore, the goal of this paper is to optimize the damping ratio for ensuring the least amount of damping [24].

IV. Bat Algorithm

The echolocation activity of bats (micro bats) is the primary inspiration behind the Bat Algorithm. There are many distinct species of bats in nature, each with its own size and weight. However, when it comes to navigation and hunting, they all exhibit quite similar habits. At night, when bats go for hunting, they generally make low, medium, and high-level sounds and hear the echoes that bounce back off an obstacle or prey. Bats utilize their unique hearing system to determine the size and location of an item. These features of bats when seeking prey have been included into the design of the BA. Keeping this echolocation feature of bats in mind, Yang [17] suggested the BA.

The stages of Bat Algorithm are summed up below:

Step 1. Initialization of the bat parameters, as shown in Table I.

TABLE I. Parameters of BA

M	The population size of bat
N	Maximum iteration number
I	Total number of bats in range [1, M]
X^*	The current global best location (solution)
X_i	i^{th} bat's position
V_i	i^{th} bat's velocity
f_i	i^{th} bat's pulse frequency that ranges between f_{min} and f_{max}
f(X)	Function for Fitness evaluation.
r_i	i^{th} bat's pulse rate
A_i	i^{th} bat's loudness
α	Parameter in range [0,1] for loudness A_i upgradation
ɣ	Parameter in range [0,1] for pulse rate r_i upgradation

Step 2. Updating of the global best position X^*, pulse velocity, position, and frequency of the i^{th} bat as follows:

$$f_i = f_{min} + (f_{max} - f_{min})\beta,$$

$$V_i^{t+1} = V_i^t + (X_i^t + X^*)*f_i,$$

$$X_i^{t+1} = X_i^t + V_i^t$$

Here, V_i^t and V_i^{t+1} denote the velocity at the time t and $t+1$ respectively. X_i^t and X_i^{t+1} represent the position at time t and $t+1$ respectively. And a random number in range [0,1] is denoted by β.

Step 3. If r_i is lower than the random number, the following equation yields a new solution for the bat:

$$X_{new} = X_{old} + \varepsilon A^t,$$

Here, A^t denotes the average loudness of all bats at time t and ε refers to a random number in range [−1, 1].

Step 4. If the randomly generated value is less than A_i and $f(X_i) < f(X^*)$, the new generated solution is approved. Then, make the following changes to A_i and r_i respectively.

$$A_i^{t+1} = \alpha A_i^t,$$

$$r_i^t = r_i^0\ [1 - e^{-ɣt}]$$

Where the loudness at the times t and $t+1$ is represented by A_i^{t+1} & A_i^t respectively; r_i^0 & r_i^t signify the elementary pulse rate and pulse rate at time t respectively; α & γ are the two fixed constant parameter both in range [0,1], used for loudness & pulse rate upgradation, respectively. Since $t \longrightarrow \infty$, $A_i^t \longrightarrow 0$ & $r_i^t \longrightarrow r_i^0$.

Step 5. Ranking of the bats according to their fitness value and determine the present best solution X^*.

Step 6. Execution of the process starting from 'Step 2' again and again till the maximum iterations has been achieved, and output the globally optimum solution.

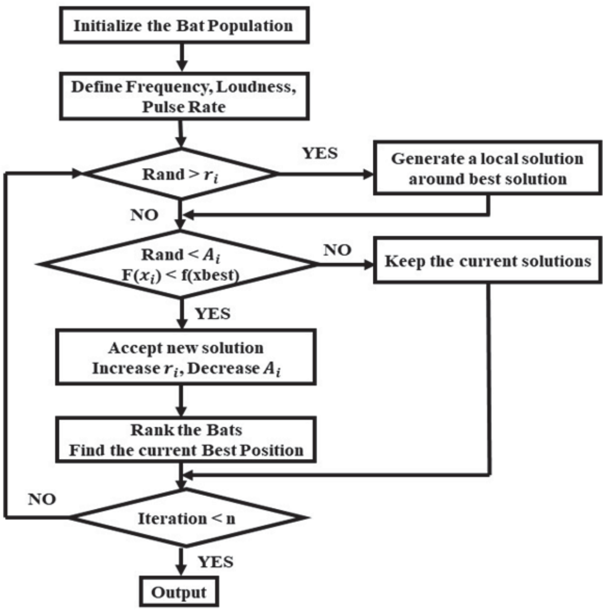

Fig. 7. General stages of Bat Algorithm

Various controller settings can give satisfactory performance. That's why control parameter tuning can be considered as an optimization problem. The suggested method uses BA to tackle this optimization problem and find the best set of UPFC parameters. Several experimental tests assessing the effect of each parameter on the final solution were conducted in this work to evaluate proper fine tuning of BA's parameters. Thus, parameters of BA are set, such as population size is 100, maximum iteration number is 500, and β=10.

V. SIMULATION RESULTS AND DISCUSSIONS

One method for observing system stability is to examine the eigen values of the system matrix. The behavior of the entire system may be predicted by observing the real part of the eigen values. The eigen value analysis is performed under three distinct loading situations (low, nominal, and heavy) by varying the values of P_e, Q_e and v_t.

TABLE II. COMPARISON OF EIGENVALUES WITH NOMINAL LOADING

Nominal loading (P_e= 0.85, Q_e= 0.1, v_t= 1.05)	
Without Optimization	***With BA***
-992.7048+0i	-998.2389+0i
-111.2156+0i	-93.06084+0i
-87.13254+0i	-2.642131+5.641642i
-6.757197+0i	-2.642131-5.641642i
-0.6078959+4.352229i	-2.228141+0.7156176i
-0.6078959-4.352229i	-2.228141-0.7156176i
-0.7021762+0.300185i	-0.3317816+0i
-0.7021762-0.300185i	-0.9629182+0i
-0.3332937+0i	-1.495628+0i

TABLE III. COMPARISON OF EIGENVALUES WITH LIGHT LOADING

Light loading (P_e= 0.5, Q_e= -0.3, v_t= 0.95)	
Without Optimization	***With BA***
-995.4846+0i	-998.6112+0i
-108.7755+0i	-93.06079+0i
-87.09233+0i	-12.85238+0i
-6.352162+0i	-1.499863+3.313434i
-0.5634133+3.701198i	-1.499863-3.313434i
-0.5634133-3.701198i	-5.419556+0i
-0.7510748+0.3630786i	-0.4430721+0i
-0.7510748-0.3630786i	-0.9514748+0i
-0.4299323+0i	-2.698959+0i

TABLE IV. COMPARISON OF EIGENVALUES WITH HEAVY LOADING

Heavy loading (P_e= 1.40, Q_e= 0.3, v_t= 1.1)	
Without Optimization	***With BA***
-991.3878+0i	-992.0988+0i
-113.0543+0i	-94.98078+0i
-86.74172+0i	-9.767012+10.8847i
-7.37079+0i	-9.767012-10.8847i
-0.3749951+4.909551i	-1.577959+1.566869i
-0.3749951-4.909551i	-1.577959-1.566869i
-0.6738931+0.273978i	-1.342706+0.4696871i
-0.6738931-0.273978i	-1.342706-0.4696871i
-0.1111021+0i	-0.1080197+0i

The simulation of a UPFC-based SMIB was carried out in this work under three loading conditions: normal, light, and heavy. The analysis of eigenvalues may be used to determine the stability of a system. The eigenvalues for both BA optimized UPFC and conventional UPFC, for three distinct loading situations, namely nominal, light, and heavy loading conditions are recorded in Tables II, III, and IV. According to the tables, all of the eigenvalues are negative, indicating that the systems are stable; nevertheless, traditional UPFC requires significantly longer time to settle down the disturbance than optimized UPFC since its complex eigenvalues are very close to the imaginary (jω) axis.

TABLE V. COMPARISON OF DAMPING RATIO FOR DIFFERENT LOADING CONDITIONS

Loading Conditions				**Minimum Damping Ratio**		
Load	***P_e (pu)***	***Q_e (pu)***	***V_t (pu)***	***Conventional UPFC***	***TSA Tuned UPFC***	***BA Tuned UPFC***
Nominal	0.85	1.00	1.05	0.1383	0.5501	0.6282
Light	0.50	-0.30	0.95	0.1505	0.4161	0.4745
Heavy	1.40	0.30	1.10	0.0762	0.3582	0.4846

The minimum damping ratios for conventional UPFC, BA-optimized UPFC and TSA-optimized UPFC under different loading conditions are presented in Table V. Based on the table, it is clear that BA optimized parameters have higher values than TSA-optimized parameters as well as the traditional ones, indicating a greater damping efficiency when using BA optimized UPFC.

According to both minimum damping ratios and eigenvalue comparisons, BA optimized UPFCs are clearly superior to TSA-optimized UPFCs and also conventional ones in terms of settling down small frequency oscillations following any disturbance experienced in a real-time power system network.

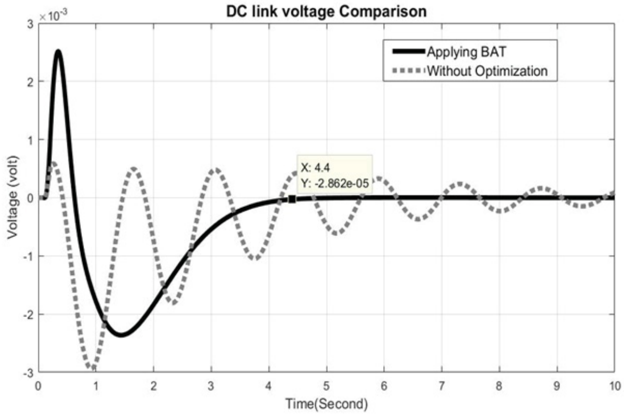

Fig. 8. DC link voltage ΔV_{DC} response curve with and without BA optimization

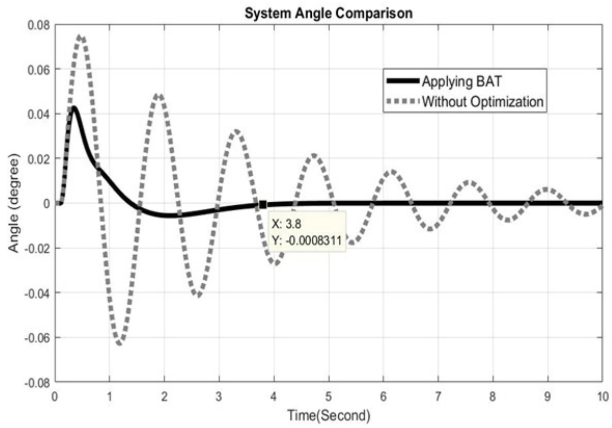

Fig. 9. Rotor Angle $\Delta\delta$ response curve with and without BA optimization

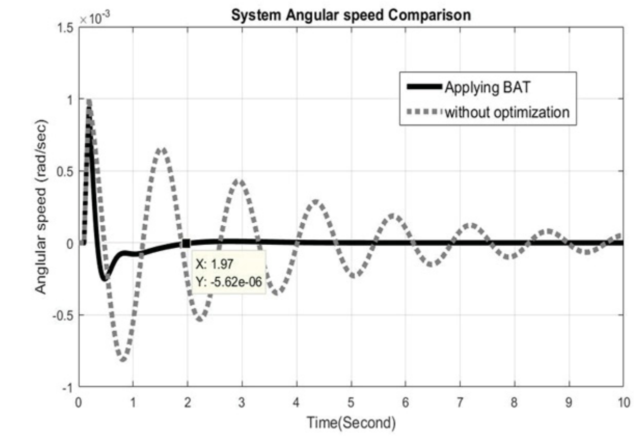

Fig. 10. Angular speed $\Delta\omega$ response curve with and without BA optimization

The findings of the time domain simulation for ten seconds following physical disruptions are depicted in the figures above. The characteristic of DC link voltage (ΔV_{DC}) is shown in Fig. 8. Fig. 9 and Fig. 10 illustrate how the machine's rotor angle ($\Delta\delta$) and angular speed ($\Delta\omega$) fluctuates over time. From these figures, it can be seen that the BA-optimized UPFC has a quicker response than the traditional UPFC. When the settings for conventional fixed gain UPFC are chosen randomly, the state's response takes a very long time to reach a stable condition. Even utilizing a standard fixed gain UPFC and a 10-s time frame in the simulation, the system could not attain a stable state which can be seen from the above three figures. When the controller parameters are improved using the suggested BA optimization, the states become stable in about 4.4 s for V_{DC} in Fig. 8, 3.8 s for $\Delta\delta$ in Fig. 5, and 1.97 s for $\Delta\omega$ Fig. 6. It clearly shows the UPFC architectures, optimized by BA, stabilize the system within a short period of time, whereas a conventional one takes much longer.

The MATLAB simulation software was used to perform the simulation work. For convergent and output to appear, it took around 9.673854 seconds.

VI. Conclusion

The primary goal of this article is to evaluate the performance of a UPFC-connected SMIB power system in real time when exposed to LFOs. To accomplish this goal, a new optimization approach known as the "BAT Algorithm" with an Eigen value-based multi-objective function is used. The performance of the proposed technique is evaluated under three distinct loading situations. The eigen value, as well as the simulation of nonlinear time domain, are being examined to show the feasibility of the proposed controller. The effectiveness of the proposed controller is also compared with a fixed gain-based traditional controller. Both the eigenvalue analysis as well as the time domain representation of system parameters clarify that the suggested controller outsails the traditional controller in every aspect. In addition, the results of the BA-optimized UPFC are compared with the well-established TSA-optimized UPFC. Comparative study shows that the BA-tuned method gives better result than the TSA-tuned method in terms of damping ratio, and the BA-tuned technique takes less time than TSA-based technique to stabilize the system. As a result, the introduced model demonstrates its effectiveness as a real-time optimizer while also ensuring resilience in power system stability enhancement. The approach provided in this research, however, may be expanded to tune the UPFC parameters of a multimachine power system network.

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