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ORIGINAL RESEARCH PAPER

Two-area power system stability analysis by frequency controller with UPFC synchronization and energy storage systems by optimization approach

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ABSTRACT

An optimization approach for two-area power system with Unified Power Flow Controller (UPFC) is proposed in this paper. The proposed method is the Atomic Orbital Search (AOS) approach. The proposed approach is applied to achieve full utilization of UPFC and keeps the parameters uncertain. The multivariable PI controller is utilized to control the system controller and eliminates the negative interaction of the controllers. The proposed approach combines the two subsystems by converting algebraic subsystem using differential approximation, which leads to a nonlinear system. The proposed approach provides efficient voltage regulation and quicker damping of inter-area mode oscillations. The proposed UPFC controller eliminates generator oscillation and fault condition, which guarantee the stability of the system as well as provides dynamic power flow control under the tie-line. At last, the proposed method is simulated on MATLAB platform and compared with existing methods. From this comparison, it is shown that the proposed approach provides less oscillation than the existing approach.

KEYWORDS

unified power flow controller, optimization approach, two area power system, PI controller, stability, uncertain parameter

1. INTRODUCTION

In the modern power system, load frequency control (LFC) is applied efficiently in recent years [1]. The main objective of LFC is to maintain the balance among the generation and consumption [2]. LFC utilizes a hierarchic topology using primary, secondary, and tertiary control. Automatic controllers, usually classic, and tuned according to operator, are carried out through primary and secondary control [3]. In the difficult situation, the tertiary control is manually implemented using transmission system operator [4]. Automatic generator control (AGC) is secondary load frequency control that plays a significant role on power system [5]. While in normal/abnormal operating conditions, the AGC provides planned values through the stabilization of network frequency and power transmission among power system areas [6, 7]. The LFC of the interconnected system is more challenging due to

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increasing size, complexity of interrelated power systems, high operating costs, limitations of traditional units, by the growing diffusion of renewable energy sources (RES) [8–12].

In LFC, tie-line power control is important, but robustness of AGC against important disturbances is not guaranteed by classical controller [13]. Flexible AC Transmission System (FACTS) devices are employed to improve control of power systems and enhance network power transmission [14]. There are various FACT devices, such as Thyristor Controlled Series Capacitor (TCSC) [15], Static Synchronous Series Compensator (SSSC), Inter-line Power Flow Controller (IPFC), Unified Power Flow Controller (UPFC) [16], and Gate Controlled Series Capacitor (GCSC), which are used to solve LFC problems. By directing actual power transfer in the tie lines, FACTS devices deliver efficient AGC performance [17]. The Busbar voltage and power flow of system are efficiently managed by SSSC [18]. UPFC is one of the efficient controllers, which is utilized to achieve power system [19].

The tie line power oscillations are mitigated by FACT devices, leading to a smoother signal to the AGC [20]. The control the voltage and power system stability is obtained by utilizing these devices [21]. The biggest benefit of the dynamic stability model of linearization is that it converts non-linear system dynamics into linear ones, which is a minimized number of linear systems [22]. Hence, autonomous power system is stable and has zero dynamics [23]. There are various adaptive control methods like Sliding mode control (SMC), fuzzy-PI Control, etc., which are utilized to design the controllers [24, 25]. The organization of the manuscript is shown in Fig. 1.

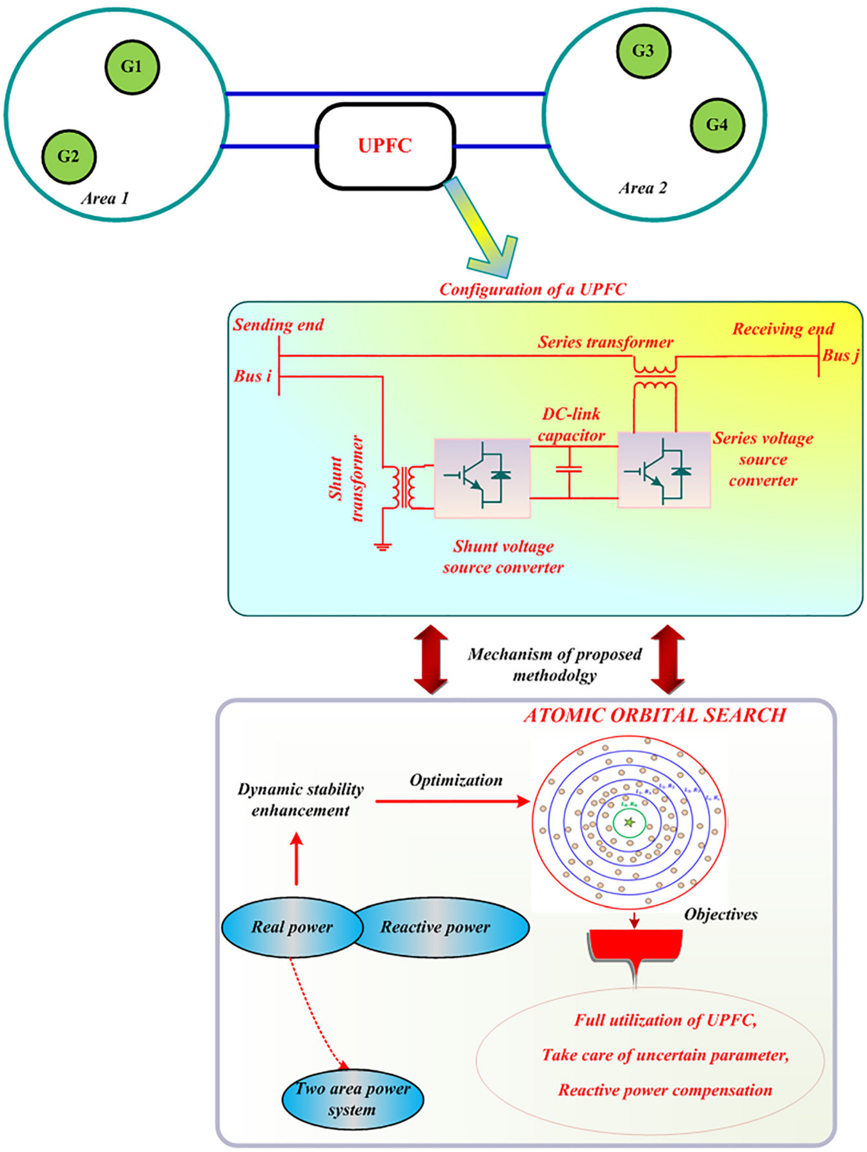

Fig. 1. Configuration of proposed interconnected power system

2. RECENT RESEARCH WORKS: A BRIEF REVIEW

Several research papers were obtainable in literature, depending on the LFC of multi-area power system. Some works are reviewed here:

Munisamy and Sundarajan [26] have described the performance of ANFIS method for LFC of three-area unsatisfactory thermal power system. The ANFIS combines the benefits of Fuzzy Logic Control (FLC) and the fast response and flexibility of artificial neural network (ANN). To recover LFC performance, the proposed controller was replicated by Superconducting Magnetic Energy Storage (SMES) units also Thyristor Controlled Phase Shifter (TCPS) separately. Sharma et al., [27] have established the LFC and it can play the main role in the PS with stand frequency of grid through the duration of rapid load demand variation. The ANFIS approach was the management of 3-area unsatisfactory thermal power system for the LFC. ANFIS controller was presented along: it combines the advantages of FLC quick reaction and flexible artificial neural network environment. Jin et al., [28] have suggested a current method like robust LFC system that was considered proficient for large-scale power system utilize time delay. The newly constraint time delayed ordinary differential equation (CTODE) miniature was presented. Depending on the newly bounded real lemma (BRL) were well-known for performance analysis H_{∞}. Stabilization and robust stability of triggered LFC an adaptive event with the sliding mode control (SMC) for multiple area power system on the network environment and it was studied by Lv et al., [29]. Triggered adaptive event method was introduced to increase the bandwidth network, and it can be modified as per the conditions. SMC was generated to provide robustness of performance and deviation frequency by unbalanced power or transmitting time delays.

Dev and Sarkar [30] demonstrated the plan of higher order SM observer (HOSMO) depending on the super targeting sliding mode control (ST-SMC) for LFC, which was an interrelated multi-area power system (MPS). The rapid load distribution on some areas may cause deviation on frequency with tie line power from its desirable values. They were designed to enhance the overall performance of the system and presented system. Zhang and Yang [31] have investigated the switching control theory and it was based on the novel decentralized LFC strategy. In variable switching declaration, the transmission delayed in the series system and it was modeled in the network of LFC system. By comparison with the existing modeling method and the approached modeled, it influences packet loss and time delay and the system dynamics are more accurate at first. The memory loss on feedback control design system was introduced in the second. Zhong et al., [32] introduced a newly event-triggered H_{∞}, LFC method, using dynamic activated algorithm for multiple area non-linear power systems (NPSs), and this approach was discussed. It differs from the present linear single area LFC and power system method was upgraded, the nonlinear multiple area was modeled. Also, it was built by considering the occurrence of long term oscillations and overshoots.

2.1. Background of research work

The literature survey demonstrates that LFC is the most significant approach to protect the system from many affecting factors, as well as to reduce the deviation of power sharing. In the present days, the utilization of large-scale renewable energy sources (RES) and their development is high. Due to the stochasticity and intermittency characteristics of the RES, the power grid stable operation is affected, specifically in terms of frequency fluctuation. Therefore, to recognize the large-scale grid connection of RES, it is significant to grow effective control approaches for charging frequency of a power system. In a large power system, more than one control area was interconnected by tie lines. A sudden load variation on any control part of an interrelated power system leads to frequency change and also power deviation from the connecting line. Unbalance between supply and load causes system frequency fluctuation that may degrade power system performance and make it difficult to control. To balance the power and preserve the stability of electrical power system, various FACT devices and optimization approaches are introduced to control the charging frequency. Some of the automatic generation controls are Teaching Learning Based Optimization (TLBO), Thyristor Controlled Phase Shifter (TCPS), Superconducting Magnetic Energy Storage (SMES), Quasi Oppositional Harmony Search (QOHS) algorithm, Firefly Algorithm (FFA), Biogeography Based optimization (BBO), State Constrained Distributed Model Predictive Control (SCDMPC), FPIDN-FOPIDN controller. One of the FACT devices is TCPS which is utilized to achieve the optimal power transmission through enhancing the phase angle arrangement of voltage but which creates larger amplitude variations and phase error. TCSC is used to reduce the transmission loss but its drawback needs the constraints which are complex for placing TCSC. The optimization of FFA provides efficient and required low iteration but the limitation of this approach is local optima. Very few methods were presented in the literature to solve this issue. These drawbacks have motivated to do this research work.

3. CONFIGURATION OF THE PROPOSED TWO AREA SYSTEM

The configuration of proposed interconnected power system is displayed in Fig. 1. The FACT device of the UPFC consists of boosting transformer, two VSC, a boost transformer together with DC link capacitor in connected parts. In each area there are two generators present.

The areas are connected through the tie line. Stability is affected by velocity variations, so velocities [33] and angles are considered. The system oscillations are eliminated by the injection of real power to the system and controlling modulation index of the series VSC of UPFC. Moment of inertia, damping ratio are uncertain parameters, which are changed by the load change. The PI controller is tuned by AOS approach for providing control signal of UPFC. The UPFC shunt converter compensates the reactive power. By the proper tuning of the PI controller, using the proposed approach minimizes the error of the system.

3.1. Modeling of Unified Power Flow Controller

A UPFC is a highly adjustable FACTS device formed by integration of static series and shunt converters connected using DC coupler, powered through DC storage capacitor. This permits a two-way flow of real power between STATCOM shunt output terminals and SSSC series output terminals. A series connected converter injects a voltage with convenient phase and phase angle [34]. A converter connected in parallel provides reactive power separately to the system. With the coupling transformer, the voltage level and phase angles of the converters are measured. The leakage reactance of the series converter transformer denotes X_{se} and the leakage reactance of the shunt converter refers X_{sh}. Two buses required to assign that UPFC transmission line. The magnitude of m, n denotes $V_m\angle\varphi_m$, $V_n\angle\varphi_n$.

Across the series connected voltage source denotes,

$$\overline{V_{se}} = V_{se}\angle\theta_{se} \tag{1}$$

here V_{se} refers the series linked voltage source, θ_{se} refers voltage angle of the series connected voltage source.

The voltage magnitude and angle are processed in convenient constraints that are designated by,

$$0 \le V_{se} \le V_{se}^{Max}, 0 \le \theta_{se} \le \theta_{se}^{Max} \tag{2}$$

The equation for injected active and reactive power may be stated with the following:

$$P_{i,UPFC} = -v_i^2\left[\sum_{q=j,k} m_{iq} b_{se,iq}\phi_{iq}\right] - 1.03\left(\sum_{q=j,k} m_{iq} v_i v_q b_{se,iq}\sin\left(\beta_{iq}+\varphi_{iq}\right) - \varphi_{iq} v_i^2 b_{se,iq}\sin\varphi\right) \tag{3}$$

$$Q_{i,UPFC} = -v_i^2\left[\sum_{q=j,k} m_{iq} b_{se,iq}\cos\varphi_{iq}\right] + Q_{sh} \tag{4}$$

$$P_{p,UPFC} = m_{iq} v_i v_q b_{se,iq}\sin\left(\beta_{iq}+\varphi_{iq}\right)\forall p = j,k \tag{5}$$

$$Q_{p,UPFC} = m_{iq} v_i v_q b_{se,iq}\cos\left(\beta_{iq}+\varphi_{iq}\right)\forall p = j,k \tag{6}$$

where per unit magnitude may be referred m of voltage sources operating in the restriction of $0 \le m \le m_{\max}$, phase angles may be stated as ϕ, the susceptance of series related converter transformer shown b_{se}.

3.2. Dynamic modeling of UPFC with two area system

Power balance is the important factor for an interconnected power system. Figure 2 displays a power system with UPFC. The UPFC is operating a role of controller for AC and DC reduces system oscillation [35]. The dynamic model of UPFC is resultant by ignoring the resistance of converters, transmission lines, generators, and transformers; hence the equation is described by.

3.3. UPFCS shunt portion model

In this model is based on the modulation index of shunt converter and phase angles. The voltage (v_3) is regulated by the UPFC Shunt converter by compensating the reactive power [36–39]. The compensation is based on PI controller tuning. The error of the system is determined by the difference between the reference and actual value of v_3. Based on the shunt VSC modulation index is described by,

$$M_{sh} = (v_{3-REF} - v_3)^*\left(k_{p1} + \frac{k_{i1}}{S}\right) \tag{7}$$

The shunt area can satisfy the demand of UPFC series section through delivering energetic power to dc link capacitor. Between the AC and shunt part of UPFC of active power flow is changed by the angle variable ψ_{sh} that is utilized to control active power. Based on PI controller, the dc voltage error is balanced by,

$$J_{sh} = (v_{dc-REF} - v_{dc})^*\left(k_{p2} + \frac{k_{i2}}{S}\right) \tag{8}$$

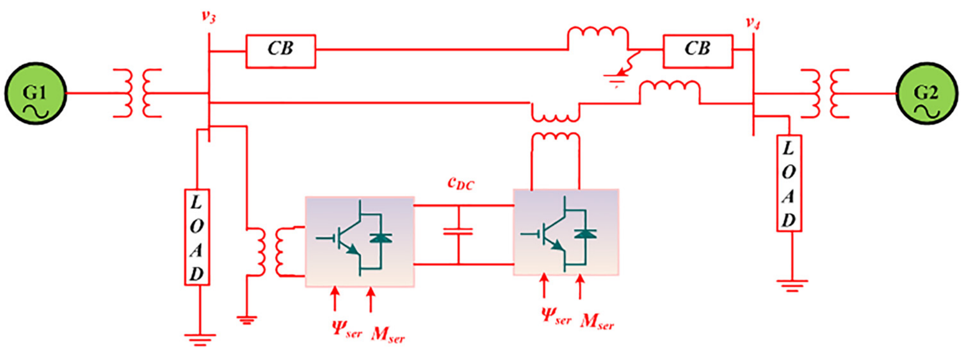

Fig. 2. Power system with UPFC

In the multi variable system, the PI control is described by,

$$\begin{bmatrix} M_{sh} \\ \psi_{sh} \end{bmatrix} = [c_p] \times \begin{bmatrix} v_{3-REF} - v_3 \\ v_{dc-REF} - v_{dc} \end{bmatrix} + \left[\frac{c_i}{S}\right] \times \begin{bmatrix} v_{3-REF} - v_3 \\ v_{dc-REF} - v_{dc} \end{bmatrix} \quad (9)$$

here c_p, c_i belongs to constant random matrix.

3.4. UPFC series portion model

The ac voltage is generated by the UPFC series portion [40–43]. The limitation of phase angle and voltage magnitude is described by,

$$\begin{cases} 0 \le \psi_{ser} \le 2\pi \\ 0 \le v_{ser} \le v_{ser}^{Max} \end{cases} \quad (10)$$

The modulation index based on series converter of UPFC is described by,

$$\dot{\psi}_{ser} = \frac{1}{l_3}(-k_a Z_1 k_i / m_1 - k_{z2} Z_2 - f_t + \dot{x}_{3s}) \quad (11)$$

here k_a, k_{z2} are design constants.

3.5. Modeling of uncertain parameter

Here, the uncertain parameter is considered as the damping coefficient which is zero at initial stage. The controller efficiency [44, 45] is improved based on the damping coefficient value. The phase angle based uncertain coefficient is defined by,

$$E_j = \alpha_j(x_1, \ldots, x_j) + \left(\overline{\phi}_j, \ldots, \phi_j\right) \quad (12)$$

Uncertain parameter based on adaptive law is described by,

$$\overset{*}{\overline{\varphi}}_j = \sum_{K=1}^{j} \frac{\partial \alpha_j}{\partial x_j} \begin{bmatrix} x_{K+1} {}^* \eta_K(x_1, \ldots x_K) + \\ f_K(x_1, \ldots x_K) \\ +\mu_J^T(x_1, \ldots x_K) \\ \left(\alpha_j(x_1, \ldots x_K) + \overline{\varphi}_j\right) \end{bmatrix} - \frac{\partial \mu_J}{\partial T} x_J \quad (13)$$

The error based on phase angle is described by,

$$\overset{*}{\varepsilon}_j = \sum_{K=1}^{j} \frac{\partial \alpha_j}{\partial x_K} \mu_K^T(x_1, \ldots x_K) \varepsilon_K \quad (14)$$

4. ROBUST STABILITY ANALYSIS OF TWO AREA INTERCONNECTED POWER SYSTEM USING UPFC

To control oscillation and maintain the uncertain parameters like phase angle and damping coefficient, this paper proposed the AOS approach. Control structure of the proposed system through linear and nonlinear controller is presented in Fig. 3. The proposed system is incorporated with linear, nonlinear controller, uncertain parameter estimator [46–49]. So, the speed and rotor angle are utilized to design the nonlinear and uncertain parameter estimator. The minimization of the oscillation of system is obtained by the nonlinear controller through the control of modulation index of series voltage source converter (series-VSC). The moment of inertia, damping ratio is calculated from the uncertain parameter estimator. The terminal voltage and dc capacitor voltage is maintained by applying the dc voltage and terminal voltage of the UPFC to the linear controller.

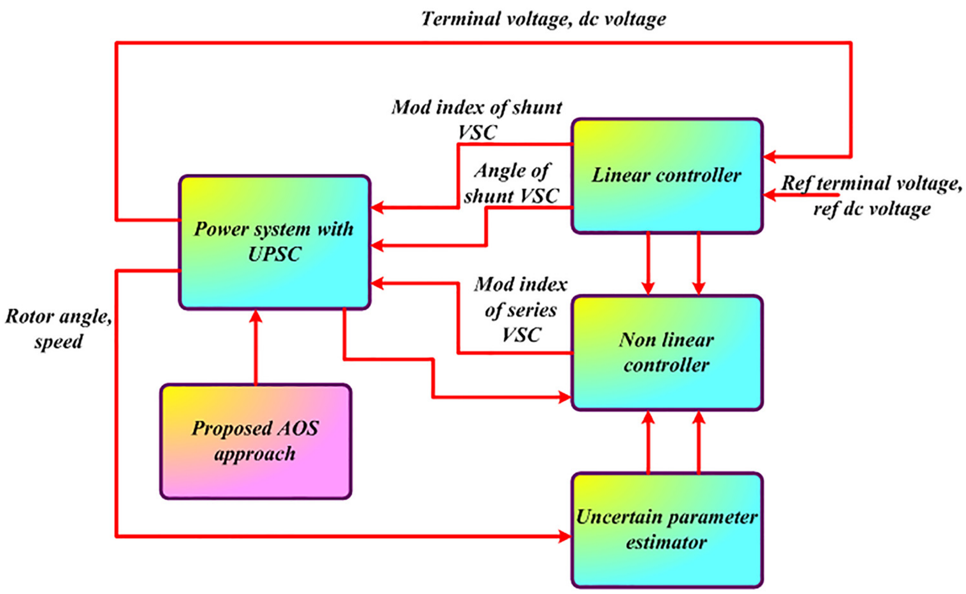

Fig. 3. Control structure of proposed system with linear and nonlinear controller

4.1. Proposed AOS approach based optimal tuning of controller

AOS is the meta-heuristic optimization approach that is stimulated via the principles of quantum mechanics activity of electrons in the nucleus of an atom [50]. The movement of electrons on embedded waves to an uncertain location was considered. It depends on the probability of location of the electrons, the orbitals are defined. For determining the probability of specific region of any electron around the atom nucleus, mathematical formulation is utilized. Depending on time, electrons immediately change their position and they act as a cloud of charge. In this work AOS is utilized to diminish the system error. The step-by-step method of the proposed approach is defined as below,

Step 1: Initiation

Initiate the input parameters as gain parameter of the PI controller, active and reactive power, dc voltage.

Step 2: Random Generation

The input parameter is generated randomly in matrix form, which is described by,

$$R(m) = \begin{bmatrix} k_p^{11}(T)k_i^{11}(T) & k_p^{12}(T)k_i^{12}(T) & \cdots & k_p^{1n}(T)k_i^{1n}(T) \\ k_p^{21}(T)k_i^{21}(T) & k_p^{22}(T)k_i^{22}(T) & . & k_p^{2n}(T)k_i^{2n}(T) \\ \vdots & \vdots & .. & \vdots \\ k_p^{m1}(T)k_i^{m1}(T) & k_p^{m2}(T)k_i^{m2}(T) & \vdots & k_p^{mn}(T)k_i^{mn}(T) \end{bmatrix} \quad (15)$$

here PI gain parameters are denoted as, $k_p^{mn}(T), k_i^{mn}(T)$.

Step 3: Evaluate the Fitness for Initial Solution

It contains random generation of input voltage and generation of fitness function; The fitness function minimizes voltage deviation among usual bus as well as fault time bus voltage. The fitness function $F(X)$ is given by,

$$F(X) = Min\{f_1\} \quad (16)$$

where

$$f_1 = \sum_{i=1}^{N_B}(V_n - V_i) \quad (17)$$

where V_n and V_i refers to the usual voltage and voltage of bus correspondingly.

Step 4: Calculate Binding State and Energy

The binding state and binding energy are computed using below equation,

$$B_s^K = \frac{\sum_{j=1}^{c} x_j^K}{c}, \begin{cases} j = 1, 2...c \\ K = 1, 2..n \end{cases} \quad (18)$$

$$B_e^K = \frac{\sum_{j=1}^{c} E_j^K}{c}, \begin{cases} j = 1, 2...c \\ K = 1, 2..n \end{cases} \quad (19)$$

here c represents number of candidates on k-th layer. Using these equations determines the best solution.

Step 5: Generate the Updating Random Parameters

The random parameters like ρ, μ, υ are generated in a random manner.

Step 6: Calculate the Photon Rate

Comparison of the different interaction photon rate is utilized; the photon rate is depending on absorption and emission of electron. Consider the random parameter (ρ) which is greater than or equal to photon rate then, the electron movement is based on absorption and emission. ρ is less than the photon rate then, the electron movement is based on interaction with particles.

$$x_{j+1}^K = x_j^K + Rand_j \quad (20)$$

here $Rand_j$ represents the random number distributed on range [0, 1].

Step 7: Compare the Energy Level to Binding Energy

Energy level is higher than the binding energy, then takes the form

$$x_{j+1}^K = x_j^K + \frac{\rho_j \times \left(\mu_j \times l_e - \upsilon_j \times B_s\right)}{K} \quad (21)$$

Energy level is lower than the binding energy, then takes the form

$$x_{j+1}^K = x_j^K + \rho_j \times \left(\mu_j \times l_e - \upsilon_j \times B_s^K\right) \quad (22)$$

Based on the above two equation, it controls the binding state and energy. Based on the comparison result, the parameters are updated.

Step 8: Find the Best Global Solution

The best global solution is determined by the binding state and binding energy. In this step, if the maximal number of iterations is gotten, the process exits from that point or else mutation and crossover operation is performed. Here, the best voltage, cost and power chromosomes are decided, taking into account the fitness values. At this position, UPFC displays that better combination of efficiency depends on generator's fault from the point of view of output combination. The output is as follows,

$$\begin{bmatrix} F(x)_{11} & F(x)_{12} & \cdots & F(x)_{1n} \\ F(x)_{21} & Fit_{22} & \cdots & F(x)_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ F(x)_{m1} & F(x)_{m2} & \cdots & F(x)_{mn} \end{bmatrix} = \begin{bmatrix} (f_1)_{11} & (f_1)_{12} & \cdots & (f_1)_{1n} \\ (f_1)_{21} & (f_1)_{22} & \cdots & (f_1)_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ (f_1)_{m1} & (f_1)_{m2} & \cdots & (f_1)_{mn} \end{bmatrix} \quad (23)$$

The UPFC capacity is chosen with AOS algorithm that is shown in the accompanying section, depending on the optimal location parameters.

Step 9: Check the Termination Criteria

If the termination criteria are fulfilled, stop the process; if not go to step 3. Flowchart of proposed AOS approach is displayed in Fig. 4.

5. RESULTS AND DISCUSSION

The performance of proposed approach depends on the simulation outcome. The proposed AOS approach is utilized to control the UPFC. The two area connected system for voltage regulation and damping the oscillation is an important factor. For this purpose, UPFC is introduced on two area power system. The proposed method is replicated on MATLAB Simulink platform. The proposed method was examined under two cases. The performance of the proposed approach is compared to self-tuning (ST), Moth Search Algorithm (MSA), and Mayfly Optimization Algorithm (MOA).

Case 1: Performance analysis of proposed system based on two area system with two generators

The performance of the proposed methodology is analyzed under two area system with two generators. Damping and voltage control for both ac and dc is the major aim of the proposed method. The voltage of the system is regulated as

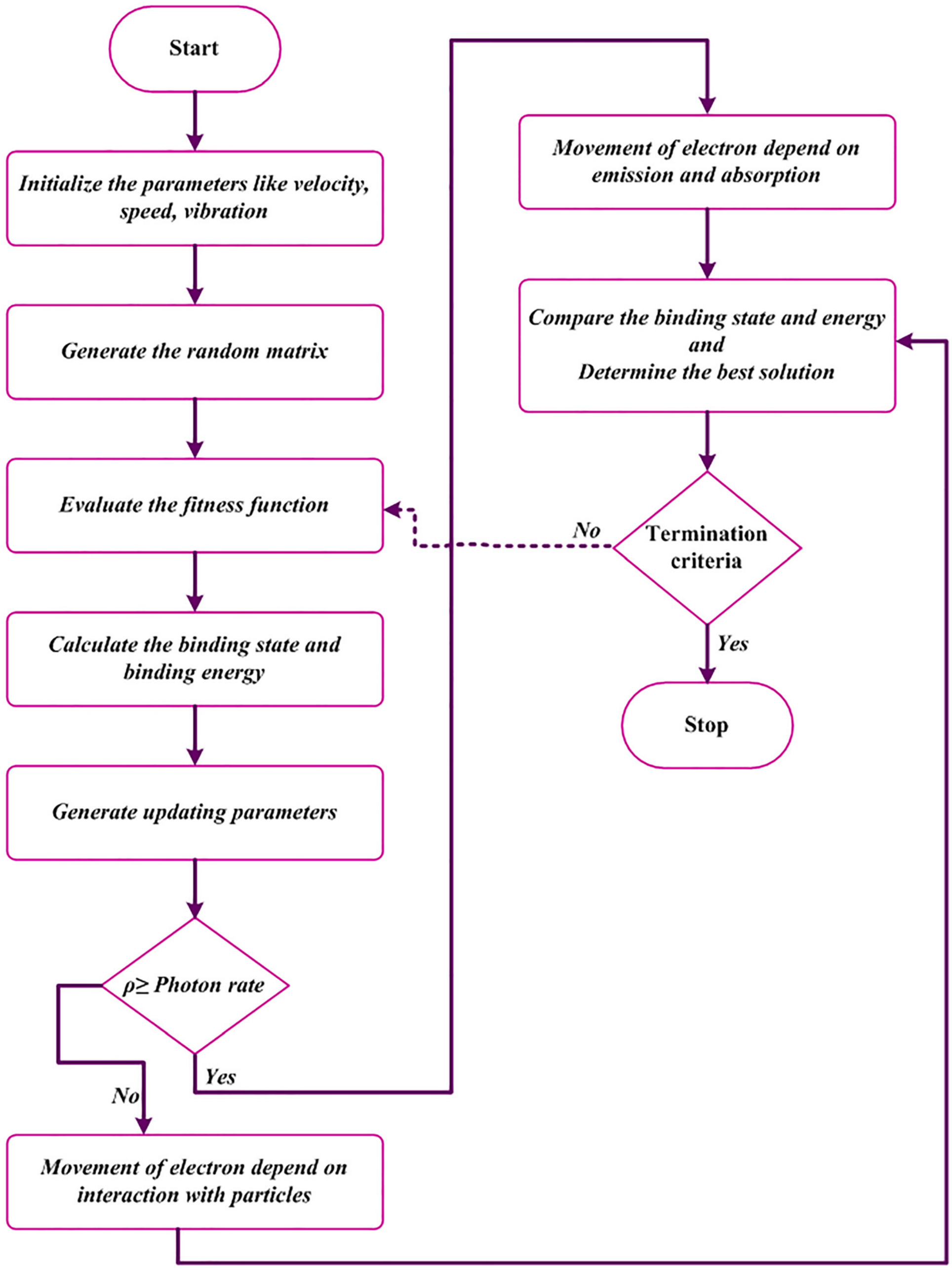

Fig. 4. Flow chart of proposed AOS approach

constant, which is clearly depicted in Fig. 5. Analysis of rotor angle variation in ac voltage controller is displayed in Fig. 6. From this Fig. 5, it can be concluded that the dc voltage reduces the error and provides constant voltage. Figure 7 display the analysis of dc terminal voltage variation in dc voltage controller. Analysis of rotor angle variation in dc voltage controller is displayed in Fig. 8. Analysis of rotor angle variation in damping controller is displayed in Fig. 9. It is concluded that the fault is cleared by the proposed approach and varied constantly.

Analysis of speed in damping controller is displayed in Fig. 10. Here the speed is 0 at 0–0.5 s and the variation occurs at 0.5–1.5 s then it is reduced to oscillate and constant at 1 $\times 10^{-3}$ (p.u) at 3.1–5 s. From Figs 11 and 12,

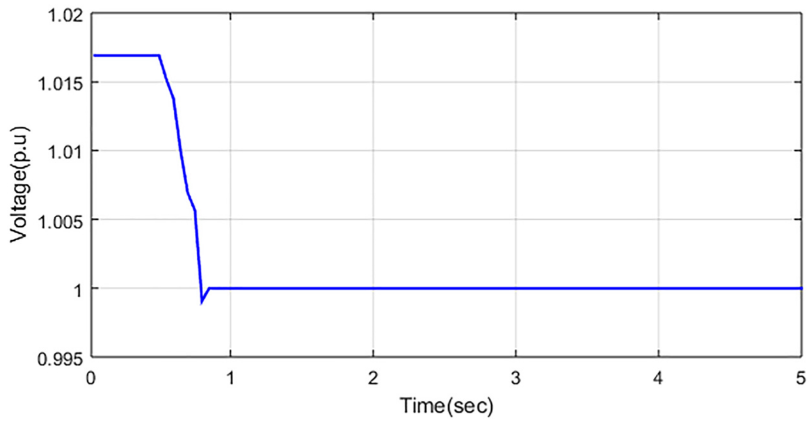

Fig. 5. Analysis of AC terminal voltage variation in ac voltage controller

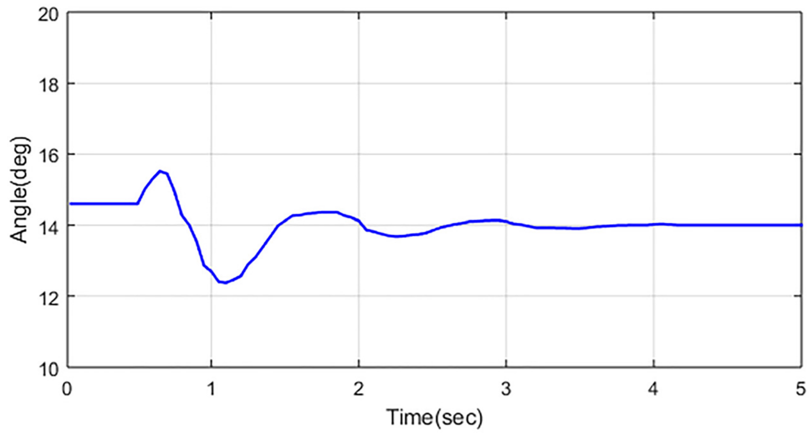

Fig. 6. Analysis of rotor angle variation in ac voltage controller

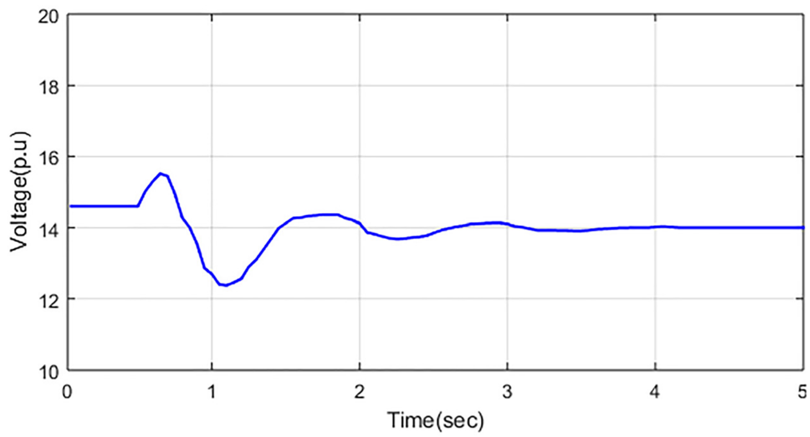

Fig. 7. Analysis of dc terminal voltage variation in dc voltage controller

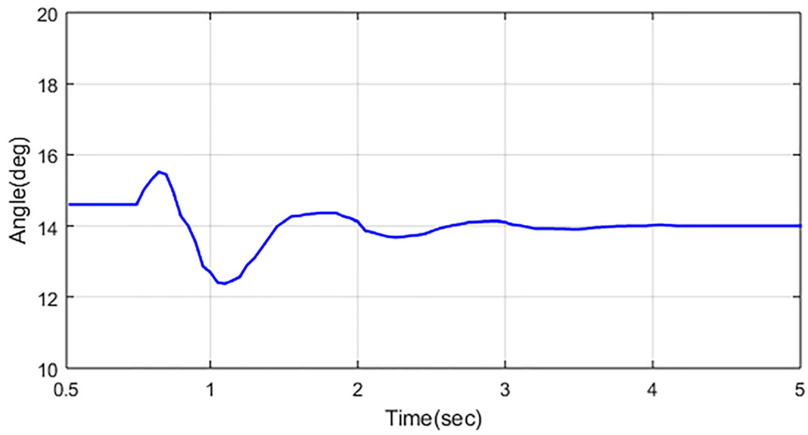

Fig. 8. Analysis of rotor angle variation in dc voltage controller

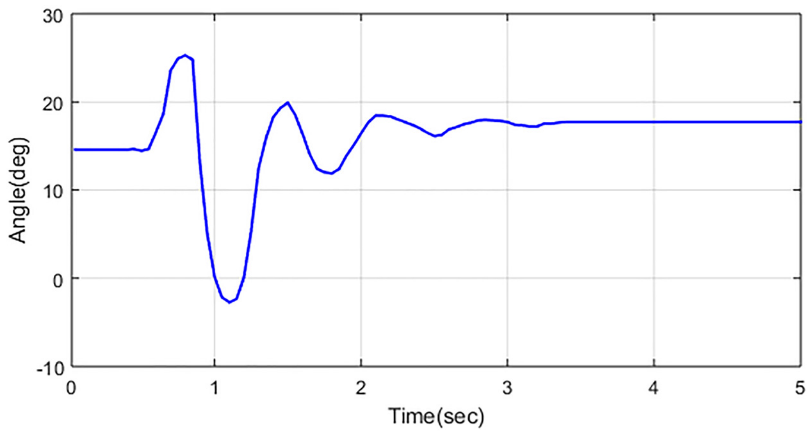

Fig. 9. Analysis of rotor angle variation in damping controller

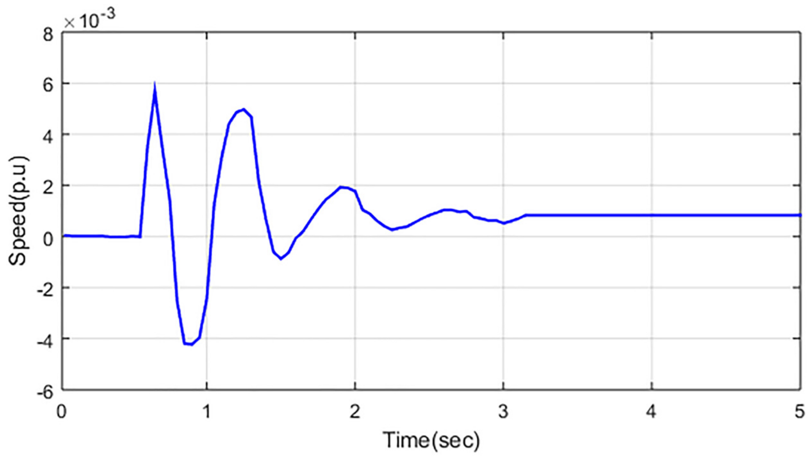

Fig. 10. Analysis of speed in damping controller

the angle difference amid two generators, change on angular speed of the generator, terminal voltage variation (v_3) are determined. Analysis of terminal voltage variation (v_3) of uncertain parameter estimator is shown in Fig. 11. Analysis of uncertain parameter of uncertain parameter estimator is shown in Fig. 12. The uncertain parameter is varied at fault condition and otherwise it becomes zero. Figures 5–12 reveals the stable closed loop system of UPFC controller in operation combined with the proposed approach.

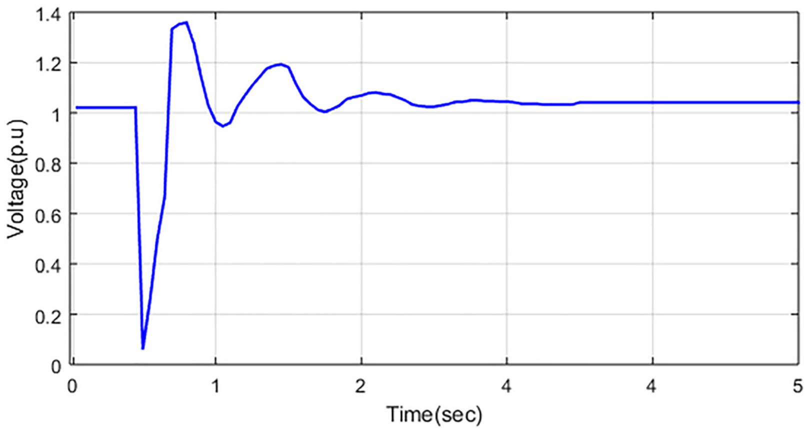

Fig. 11. Analysis of terminal voltage variation of uncertain parameter estimator

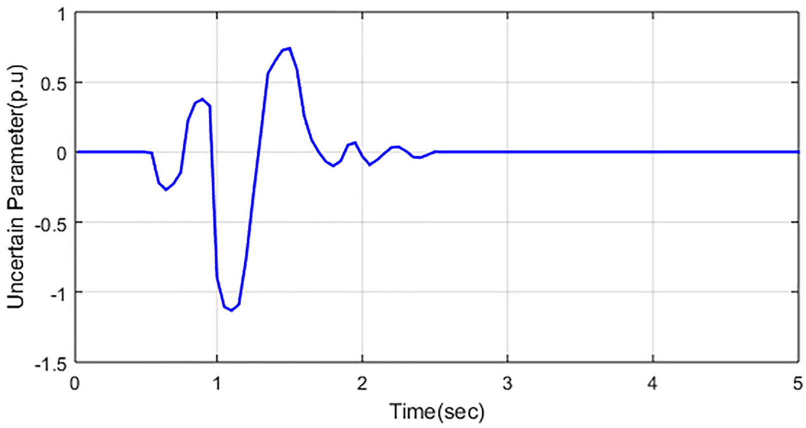

Fig. 12. Analysis of uncertain parameter of uncertain parameter estimator

Case 2: Performance analysis of proposed system based on two area system using four generators

The performance of proposed methodology is analyzed under two area system using four generators. Consider the fault is occurred in the transmission line 7 to 8. Figure 13 shows the two-area system with four generators. Analysis of inter-area oscillations is displayed in Fig. 14. Subplot 14(a) displays the load angle analysis at variation generator 1 to 3. Subplot 14(b) displays the load angle variation analysis at generator 2 to 3. Analysis of terminal voltage of voltage controller (v_7) is displayed in Fig. 15. Analysis of dc voltage variation of voltage controller is displayed on Fig. 16. From Fig. 16, it is concluded that the proposed approach efficiently operates under the fault condition.

Comparison of terminal voltage variation of voltage controller (v_7) with proposed and existing methodologies is displayed in Fig. 17. By comparing to the oscillation at 2–8 s, the proposed approach provides less oscillation, which means it varied up to 1.15 (p.u) but the existing approaches varied up to 1.22 (p.u). From this comparison, it is shown that the proposed approach delivers less oscillation to the current one. Analysis of power flow through the transmission line of 7–8 is displayed in Fig. 18. The

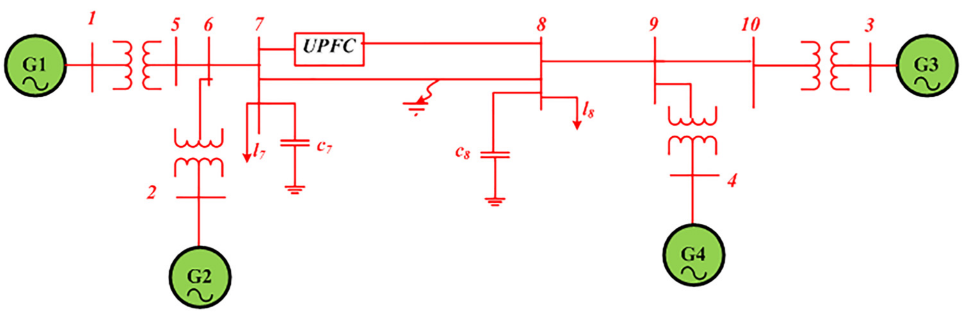

Fig. 13. Two area system using four generator

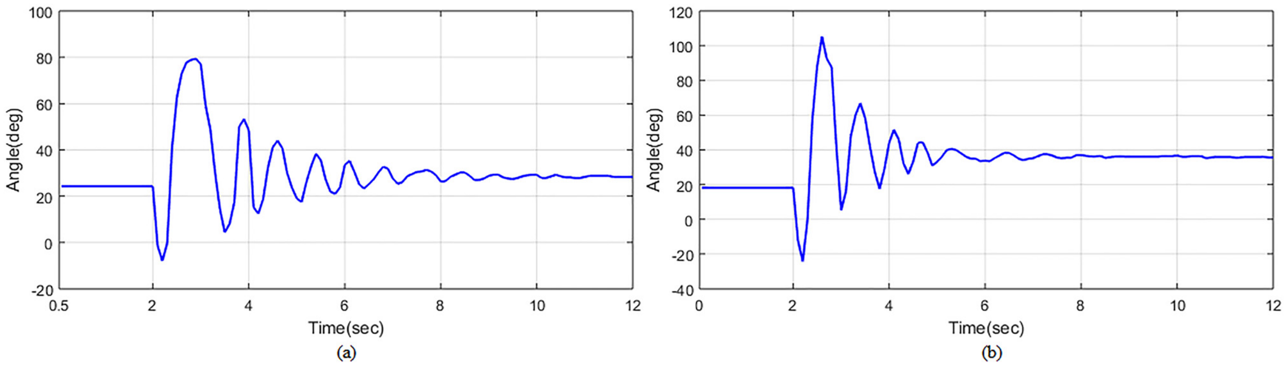

Fig. 14. Analysis of inter-area oscillations (a) load angle variation generator 1 to 3 (b) load angle variation of generator 2 to 3

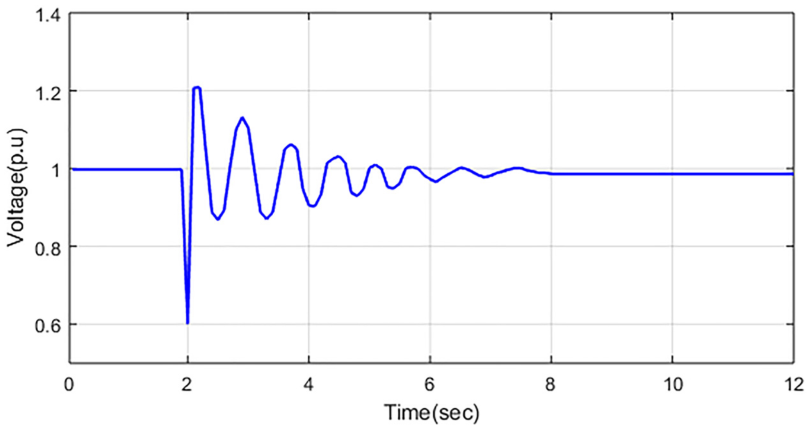

Fig. 15. Analysis of terminal voltage of voltage controller (v_7)

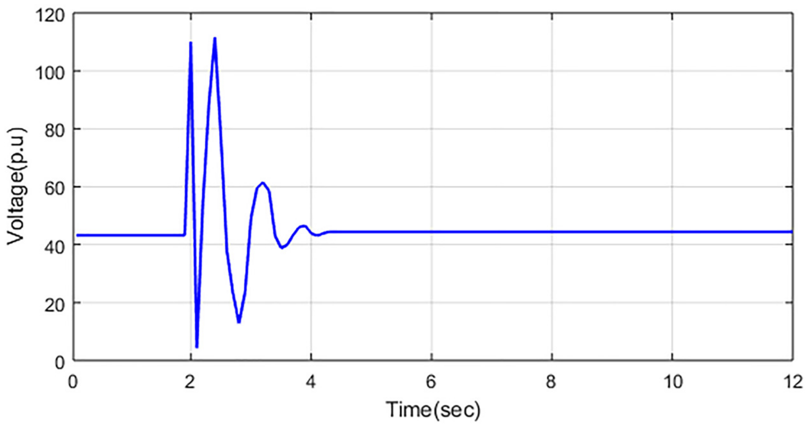

Fig. 16. Analysis of dc voltage variation of voltage controller

power is constant at 205 MW at 0–2 s, then it oscillates up to 262 MW at 2.5 s, then the oscillation is reduced and it is constant at 215 MW at 7–12 s.

Case 3: Performance analysis of proposed system based on complex power network

In this section the performance of the proposed approach depends on complex network, it consists of many generators and buses. Analysis of rotor angle variation of damping controller is displayed in Fig. 19. Subplot 19(a) displays the generator 4 angle. Subplot 19(b) displays the generator 5 angle.

Analysis of rotor angle variation of damping controller is displayed in Fig. 20. Subplot 20(a) displays the generator 6 angle. Subplot 20(b) displays the generator 7 angle. From the analysis, it is clearly depicted that the proposed approach is efficiently operating under fault condition and the proposed controller obtained proper control signal for operating the system.

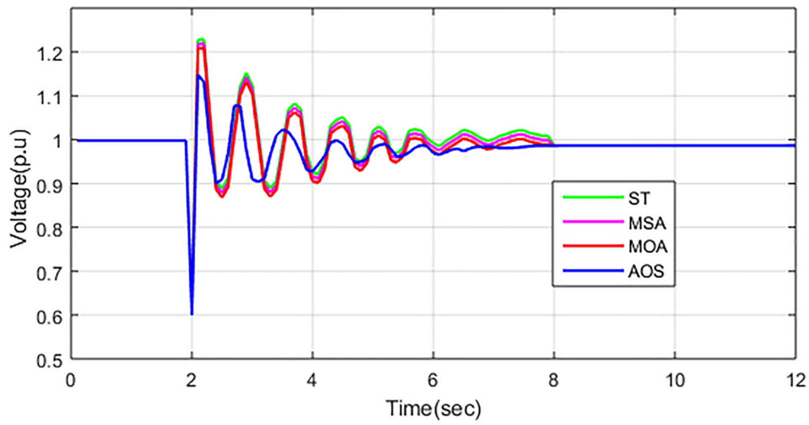

Fig. 17. Comparison of terminal voltage of voltage controller (v_7) with proposed and existing methodologies

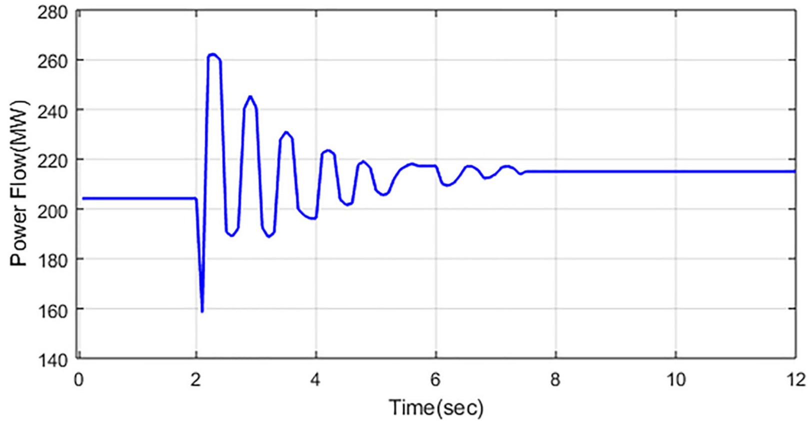

Fig. 18. Performance of power flow through the transmission line of 7–8

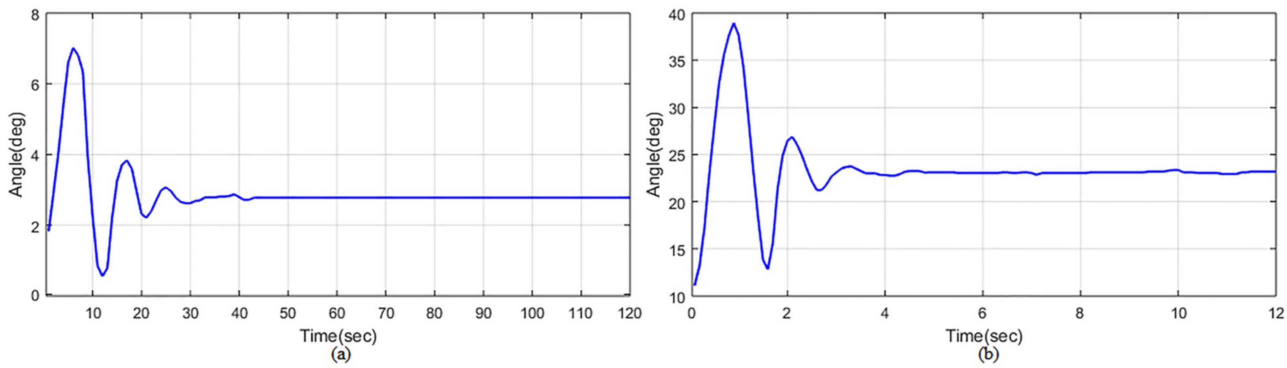

Fig. 19. Analysis of rotor angle variation of damping controller (a) generator 4 (b) generator 5

Statistical analysis of the proposed and existing approach is tabulated in Table 1. The proposed approach best and worst values become 124.65, 103.62. The existing MOA approach best and worst value become 125.24, 134.55. The best and worst values of the existing MSA approach become 135.77 and 147.66, respectively. The mean value of proposed approach is 122.185, which is less than that of the other approaches. From Table 1, it is concluded that the proposed methodology is better than the current one. Table 2 tabulated the accuracy of the proposed and existing method. The accuracy of the proposed method is better than the current one, as seen from Table 2.

The computed lessening time authenticates the decreased problems of the planned system. From this obtained outcome, the RA for entire systems is determined using Equation (24).

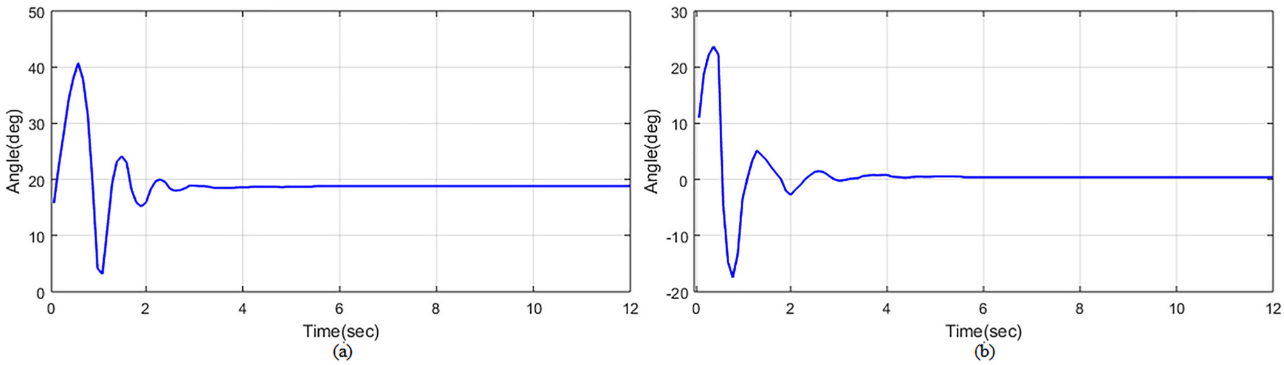

Fig. 20. Analysis of rotor angle variation of damping controller (a) generator 6 (b) generator 7

Table 1. Statistical analysis

Solution techniques	Statistical Analysis				
	Best	Worst	Mean	Median	Standard deviation
ST	143.75	160.65	154.82	157.83	147.13
MSA	135.77	147.66	142.79	142.258	141.26
MOA	125.24	134.55	132.56	147.22	2.41
Proposed	124.65	103.62	122.185	121.135	2.31

Table 2. Accuracy profile of proposed with existing techniques

Cases	Proposed technique	MOA	MSA	ST
Case 1	2	1	1	1
Case 2	2	0.4	0.2	1
Case 3	1	0.1	0.1	0.05

$$RA = \frac{ML - NL}{NL} \times 100 \quad (24)$$

here *ML* and *NL* refers to the best minimal and normal power loss at same time, the RA for several systems refers in Table 3. For obtaining correct fraction through the optimization process. Benefit is obtained through greater RA values. The ST consists of 9.666% RA value as better minimal power and normal power loss, i.e., 11.996%. The proposed hybrid system subsidizes a higher RA under optimization method, i.e. 20.116%. We may simply check that the planned system involves minimal power loss through fault conditions. It clearly demonstrated that the proposed system efficiently reduces the fluctuations at a normal level. The control process of the planned systems is better than conventional systems in preserving the intensive support of power system.

Table 3. Performance assessment of proposed system

Methods	RA (%)
ST	9.666
MSA	11.996
MOA	10.722
Proposed	20.116

6. CONCLUSION

An efficient Atomic Orbital Search (AOS) is proposed for the efficient operation of two area interconnected power systems through UPFC. UPFC is operating like a stabilizing controller. By using the proposed approach, PI controller parameters are optimally tuned and provide the control signal to UPFC. Due to the operation of the proposed approach, the error of the dc voltage and terminal voltage of the system was minimized. The proposed approach efficiently regulates the voltage and faster damping of oscillations under inter-area mode. The proposed UPSC controller eliminates the oscillation of generator and fault condition, which guarantee the stability of the system as well as provide dynamic power flow control on tie-line. The proposed method is replicated on MATLAB Simulink platform and compared to various existing approaches like ST, MSA, and MOA. The efficiency of the proposed method is examined under three cases such as complex power network, two area systems with four generators, two area systems with two generators. The proposed approach is analyzed based on the ac controller, dc controller and damping controller. The oscillations among the inter area are analyzed; the proposed approach provides less oscillation than the current one. The proposed UPFC controller minimizes the oscillation of generator under fault condition, which guarantees the stability of the system as well as provides dynamic power flow control on tie-line. Compared to the existing approach, the proposed approach provides faster damping oscillation than the current one, from the simulation outcome. In future, the experimental prototype of the proposed work will be investigated. Recent developments on capacity expansion systems and future trends in UPQC application, to cope with expanding DG capacity, are also reviewed.

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