Optimal STATCOM Design via Flower Pollination Approach for A Multimachine Power System

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Abstract: - A new metaheuristic method, the Flower Pollination Approach (FPA), based on the pollination process of flowers is proposed in this article for the optimal design of a static synchronous compensator (STATCOM) in a multimachine environment. The STATCOM parameter tuning process is converted to an optimization problem which is solved by FPA. The performance of the proposed FPA-based STATCOM (FPASTATCOM) is compared with Genetic Algorithm (GA) based STATCOM (GASTATCOM) under various operating conditions and disturbances. The superiority of the proposed technique in damping oscillations is confirmed via eigenvalues and time domain simulation results over the GA.

Key-Words: - Flower Pollination Approach, GA, STATCOM, Power System, Stability, Multimachine.

Received: October 7, 2022. Revised: September 23, 2023. Accepted: Ocotber 24, 2023. Published: November 28, 2023.

1 Introduction

The recent development of high-power electronics presents the use of Flexible AC Transmission Systems (FACTS) controllers in power systems, [1]. Subsequently, it has been demonstrated that variable shunt compensation is highly effective in both controlling power flow in the lines and hence the system voltage profile and stability, [2], [3]. Static synchronous Compensator (STATCOM) is a member of the FACTS family that is connected in shunt with the power system, [4]. By controlling the magnitude of the STATCOM voltage, the reactive power exchanges between the STATCOM and the transmission line and hence the amount of shunt compensation in the power system can be controlled. In addition to reactive power exchange, a properly controlled STATCOM can also provide great damping to the power system oscillations, [3], [4].

Recently, Artificial Intelligence (AI) techniques have been discussed in the literature to solve problems related to STATCOM design. Artificial Neural Network (ANN) for designing STATCOM is addressed in, [5], [6], [7], [8]. The ANN approach has its own merits and demerits. The performance of the system is improved by the ANN-based controller, but the main problem of this controller is the long training time, the selection of several layers, and the number of neurons in each layer. Another AI approach Fuzzy Logic Control (FLC) has received much attention in control applications. In contrast with the conventional techniques, FLC formulates the control action of a plant in terms of linguistic rules drawn from the behavior of a human operator rather than in terms of an algorithm synthesized from a model of the plant, [9], [10], [11]. However, it can be designed based on linguistic information obtained from the previous knowledge of the control system and gives better performance results than the conventional controllers; hard work is inevitable to get effective signals when designing FLC. Robust techniques, [12], [13], [14], have been also used for STATCOM design, but these methods are iterative and sophisticated and the system uncertainties should be carried out in a special format. On the other hand, the order of the controllers is as high as that of the plant. This gives rise to the complex structure of such controllers and reduces their applicability.

Global optimization techniques have been applied to the STATCOM design problem. The optimal design of STATCOM via Genetic Algorithm (GA) is developed in, [15], [16], [17], [18], [19], but, it requires a very long run time depending on the size of the system under study.

Also, it gives rise to repeat revisiting of the same suboptimal solutions. STATCOM parameters tuning using Particle Swarm Optimization (PSO) are illustrated in, [20], [21], [22], [23], [24], but it pains from the partial optimism. Moreover, the algorithm cannot work out the problems of scattering and optimization. Furthermore, the algorithm suffers from slow convergence in the refined search stage, and weak local search ability, and the algorithm may lead to possible entrapment in local minimum solutions. Artificial Bee Colony (ABC) was developed in, [25], to design a STATCOM controller, but it is slow to converge and the processes of exploration and exploitation contradict each other, so the two abilities should be well balanced for achieving good optimization performance. A relatively newer evolutionary computation algorithm, called Bacteria Foraging (BF) scheme has been established recently by, [26], [27], [28], [29], [30], [31], [32]. The BF algorithm depends on random search directions which may lead to delay in reaching the global solution.

To overcome these drawbacks, FPA is proposed in this article for the optimal design of STATCOM parameters. The problem of a robust STATCOM design is formulated as an objective optimization problem and a CS algorithm is used to handle it. The effectiveness of the proposed FPASTATCOM is tested on a multimachine power system under various operating conditions in comparison with GASTATCOM and open loop STATCOM (without supplementary signal) via eigenvalue and time domain analysis. Results evaluation show that the proposed algorithm attains good robust performance for suppressing the low-frequency oscillations under various operating conditions and disturbances

2 Problem Formulation

2.1 Power System Model

A multimachine system that consists of three generators and nine buses, is considered here. The system data and loading events are given in, [33]. Each generator is represented by the third-order model and equipped with a static exciter (IEEE type STI). The electromechanical swing equations, the generator internal voltage equation, and the exciter equation for one machine are given below:

$$\dot{\delta} = \omega - 1 \tag{1}$$

$$\tau_j \dot{\omega} = T_m - T_e - D\omega \tag{2}$$

$$\dot{E}'_q = \frac{1}{\tau'_{do}}(E_{fd} - E'_q) + \frac{(X_d - X'_d)}{\tau'_{do}} I_{td} \tag{3}$$

$$\dot{E}_{fd} = -\frac{1}{T_A} E_{fd} + \frac{K_A}{T_A}(V_{ref} - V_t) \tag{4}$$

2.2 STATCOM Dynamic Model

The power circuit of STATCOM is composed of a boosting transformer, three-phase GTO-based VSCs, and a DC capacitor link, [34], [35]. c, ψ are the amplitude modulation ratio and phase angle of the control signal of each VSC respectively, which are the input control signals to the STATCOM as shown in Figure 1. The parameters of STATCOM are given in Appendix.

The DC voltage dynamic equation is given below:

$$\dot{V}_{DC} = \frac{c}{C_{DC}}\{I_{Loq}\cos\psi + I_{Lod}\sin\psi\} \tag{5}$$

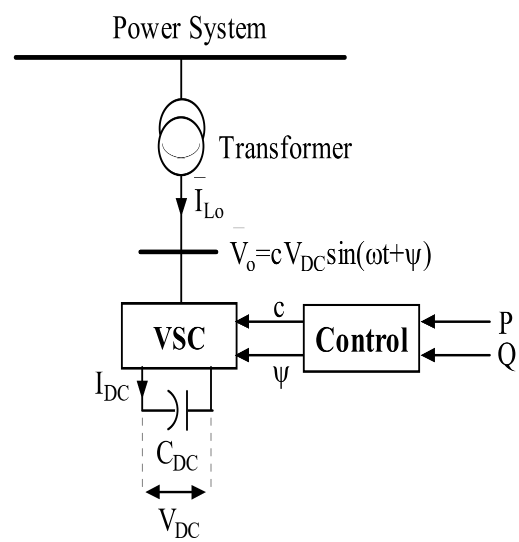

Fig. 1: Active and reactive power control of STATCOM.

DC Voltage Regulator

The DC voltage regulator controls the DC voltage across the DC capacitor. Figure 2. shows the dynamic model of the DC voltage regulator, which adopts the PI controller. The DC voltage regulator exchanges the active power between the STATCOM and the power system, [36], [37], [38]. As ψ it increases, more active power is sent to the power system from the STATCOM. The DC voltage regulator dynamic equation is given below:

$$\psi = (Kp_{dc} + \frac{Ki_{dc}}{S})(\frac{ST_c}{(1+T_c S)})(V_{DCref} - V_{DC}) \quad (6)$$

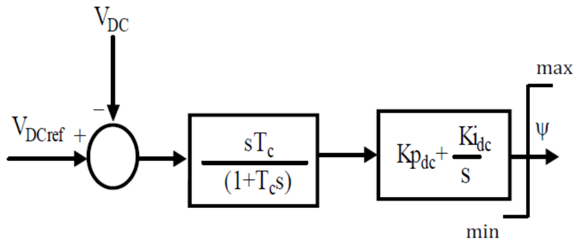

Fig. 2: Dynamic model of DC voltage regulator.

AC Voltage Regulator with Supplementary Signal

The AC voltage regulator controls the reactive power exchange with the power system. A supplementary signal can be imposed on the AC voltage control signal of the STATCOM as shown in Figure 3, where the feedback signal for the supplementary controller is the local speed deviation, [34], [35], [36]. The function of the supplementary signal is to counteract the negative damping effect brought by the interaction of both AC and DC regulators. The AC voltage regulator dynamic equations are given below:

$$c = (Kp_{ac} + \frac{Ki_{ac}}{S})(\frac{ST_{c1}}{(1+T_{c1}S)})(V_{Lref} - V_L + V_S) \quad (7)$$

$$V_S = K(\frac{1+ST_1}{1+ST_2})(\frac{1+ST_3}{1+ST_4})(\frac{ST_w}{(1+T_w S)})(\omega) \quad (8)$$

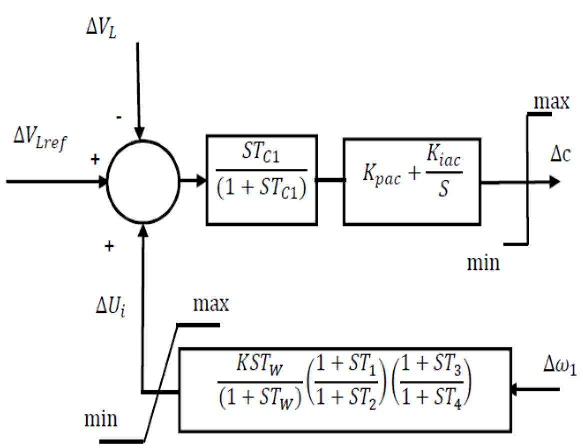

Fig. 3: Block diagram of AC voltage regulator with supplementary signal.

Bus 4 is the most sensitive bus due to the lowest maximum loadability point and Hopf bifurcation, [39], [40], [41], [42]. Moreover, it is the lower voltage profile. Finally, this location agrees with that obtained in, [29], [30].

3 Objective Function

A performance index can be defined by the Integral of Time multiplied by the Absolute Error (ITAE) of the speed deviation of each generator and DC voltage link. The merit of this chosen performance index is that minimal dynamic plant information is required. Other indices, the Integral of Square Error (ISE) and Integral of Time Multiply Squared Error (ITSE) are very offensive criteria because squaring the error creates unrealistic evaluation. Also, the Integral of Absolute Error (IAE) is unqualified compared with the ITAE which illustrates a more realistic error-index, [43], [44].

Accordingly, the objective function J is set to be

$$J = \int_0^{t_{sim}} t\left\{\left|\Delta\omega_1 + \Delta\omega_2 + \Delta\omega_3\right| + \left|\Delta V_{DC}\right|\right\} dt \quad (9)$$

The values of the washout time constants T_W, T_c and T_{c1} are kept at 10, 8, and 8 seconds respectively. The values of time constants T_2 and T_4 are fixed at a reasonable value of 0.05 second. Typical ranges of the optimized parameters are [1-100] for K, Kp_{dc}, Ki_{dc}, Kp_{ac}, Ki_{ac}, and [0.06-1.0] for T_1 and T_3. Optimization problem based on the objective function J can be stated as: minimize J subjected to:

$$K^{min} \le K \le K^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$Kp_{ac}^{min} \le Kp_{ac} \le Kp_{ac}^{max}$$
$$Ki_{ac}^{min} \le Ki_{ac} \le Ki_{ac}^{max}$$
$$Kp_{dc}^{min} \le Kp_{dc} \le Kp_{dc}^{max}$$
$$Ki_{dc}^{min} \le Ki_{dc} \le Ki_{dc}^{max} \quad (10)$$

The optimization aims to search for the optimal set of STATCOM parameters via CS that reflect the settling time and overshoots of the system. Furthermore, the aims are enhancing the damping characteristics, acquiring a good performance under different operating conditions, and improving the voltage profile of the system.

4 Overview of FPA

FPA was developed by, [45]. It is inspired by the pollination process of flowers. Real-world design problems in engineering are usually multiobjective. These multiple objectives conflict with one another. FPA has been adopted here to solve the problem of STATCOM design.

4.1 Characteristics of Flower Pollination

The main purpose of a flower is reproduction via pollination. Flower pollination correlates with the transfer of pollen, which is often associated with pollinators. Indeed, some flowers and insects have a very specialized flower-pollinator sharing, [46]. Pollination can be achieved by self or cross-pollination. In addition, bees and birds may follow Lévy flight behavior in which they fly distance steps obeying a Lévy distribution. Also, flower constancy is considered as an incremental step using the similarity of two flowers, [47]. The objective of flower pollination is the survival of the fittest and the optimal reproduction of plants. This can be considered as an optimization process of plant species. All of these factors created optimal reproduction of the flowering plants.

4.2 Flower Pollination Algorithm

For FPA, the following four steps are used:

Step 1: Global pollination represented in biotic and cross-pollination processes, as pollen-carrying pollinators fly following Lévy flight, [45].

Step 2: Local pollination is represented in abiotic and self-pollination as the process does not require any pollinators.

Step 3: Flower constancy which can be developed by insects, which is on par with a reproduction probability that is proportional to the similarity of the two flowers involved.

Step 4: The interaction of local and global pollination is controlled by $p \in [0,1]$, lightly biased toward local pollination.

The previous steps have to be converted to suitable updating equations. For example at the global pollination step, the pollinators carry the flower pollen gametes, so the pollen can travel over a long distance. Therefore, global pollination and flower constancy step can be represented by:

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) \qquad (11)$$

Where x_i^t is the pollen i, and g_* is the current best solution found among all solutions at the current generation. Here γ is a scaling factor controlling the step size.

The Lévy flights are based on step size that corresponds to the strength of the pollination. Since long distances can be covered by insects using various distance steps, a Lévy flight can be used to mimic this behavior. That is, $L > 0$ from a Lévy distribution.

$$L \sim \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda / 2)}{\pi} \frac{1}{s^{1+\lambda}} \quad (s > s_0 > 0) \qquad (12)$$

$\Gamma(\lambda)$ is the standard gamma function, and this distribution is valid for large steps $s > 0$.

For the local pollination, both Step 2 and Step 3 can be represented as

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \qquad (13)$$

where x_j^t and x_k^t are pollen from different flowers of the same plant species mimicking the flower constancy in a limited neighborhood. For a local random walk, x_j^t and x_k^t comes from the same species and then ε is drawn from a uniform distribution as [0, 1].

Flower pollination activities can occur at all scales. However, adjacent flower patches are more likely to be pollinated by local flower pollen than those far away. To mimic this, one can use a switch probability to switch between common global pollination to intensive local pollination. The flowchart of FPA is given in Figure 4 (Appendix). The data of FPA is shown in the appendix.

5 Results and Simulations

In this section, the superiority of the proposed FPA algorithm in designing STATCOM compared with optimized STATCOM with GA and open loop STATCOM (DC and AC regulators) is illustrated.

Table 1, shows the system eigenvalues and damping ratio of mechanical modes with three different loading conditions. It is clear that the FPASTATCOM shifts the electromechanical modes to the left of the S-plane, and the values of the damping factors with the proposed FPASTATCOM are significantly enhanced for different loading conditions. Also, the damping ratios corresponding to FPASTATCOM controllers are larger than those corresponding to GASTATCOM and open loop STATCOM. Hence, compared with GASTATCOM and open loop, FPASTATCOM provides good robust performance and achieves superior damping characteristics of electromechanical modes. Results of FPASTATCOM parameters set values based on the proposed objective function using FPA and GA are given in Table 2.

Table 1. Mechanical modes and ζ under different loading conditions and controllers

	GASTATCOM	FPASTATCOM
Light load	-1.43 ± 6.53j,0.21	-1.13 ± 6.92j,0.16
	-1.09 ± 6.92j,0.155	-2.16 ± 6.05j,0.34
	-1.4 ± 5.6j,0.243	-1.51 ± 5.68j,0.26
Normal load	-1.35 ± 9.07j,0.147	-1.43 ± 9.1j,0.155
	-1.28 ± 7.9j,0.16	-1.69 ± 7.7j,0.21
	-0.91 ± 5.77j,0.156	-1.7 ± 5.7j,0.29
Heavy load	-1.06 ± 10.81j,0.1	-1.16 ± 10.56j,0.11
	-0.92 ± 8.56j,0.11	-0.99 ± 8.25j,0.12
	-1.14 ± 5.6j,0.2	-1.37 ± 5.27j,0.25

Table 2. Parameters of STATCOM for different algorithms

		FPA	GA
DC Regulator	Kp_{dc}	18.0959	12.0959
	Ki_{dc}	23.4575	49.4575
AC Regulator	Kp_{ac}	55.3694	65.3694
	Ki_{ac}	25.9627	35.9627
Supplementary Signal	K	49.4526	42.3005
	T_1	0.6875	0.2475
	T_3	0.4168	0.6801

5.1 Response under Normal Load Condition

The validation of the system performance due to a 20% increase of mechanical torque for generator 1 as a small disturbance is verified. Figure 5 and Figure 6, show the response of $\Delta\omega_{12}$, and $\Delta\omega_{13}$ due to this disturbance under normal loading conditions. It can be seen that the system with the proposed FPASTATCOM is more stabilized than GASTATCOM and open loop. In addition, the required mean settling time to mitigate system oscillations is approximately 1.05 seconds with FPASTATCOM and 1.6 seconds for GASTATCOM.

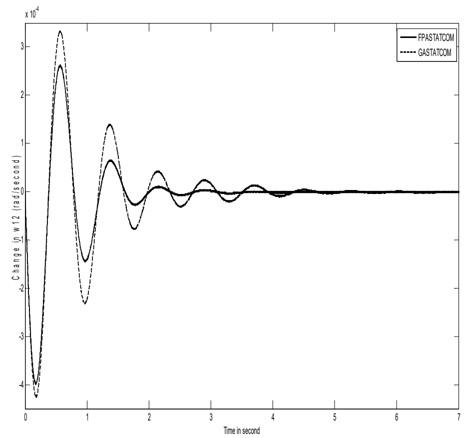

Fig. 5: Change of $\Delta\omega_{12}$ under normal condition.

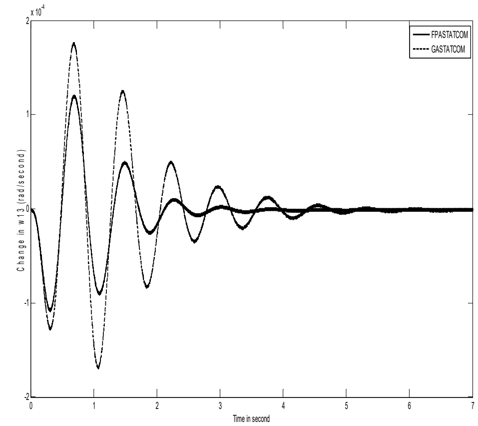

Fig. 6: Change of $\Delta\omega_{13}$ under normal condition.

5.2 Response under Light Load Condition

Figure 7 and Figure 8, show the system response under light loading conditions with fixing the controller parameters. It is clear from these figures, that the proposed FPASTATCOM has good damping characteristics to system oscillatory modes and stabilizes the system rapidly. Also, the mean settling time of oscillations is T_s=1.46 and 2.6 seconds for FPASTATCOM and GASTATCOM respectively. In addition, the system with open loop STATCOM cannot reach a steady state value till 12 seconds. Hence, the proposed FPASTATCOM outlasts GASTATCOM and the open loop controller in attenuating oscillations effectively and minifying settling time. Consequently, the proposed FPASTATCOM extends the power system stability limit.

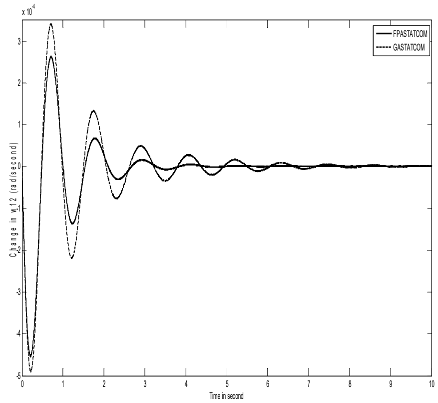

Fig. 7: Change of $\Delta\omega_{12}$ under light condition.

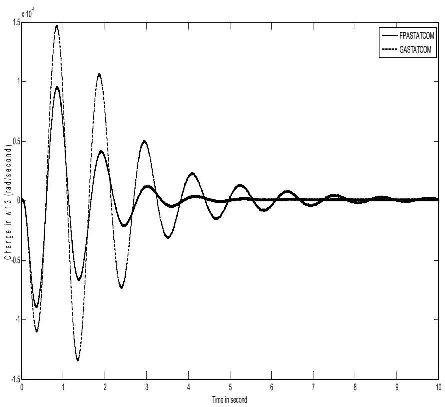

Fig. 8: Change of $\Delta\omega_{13}$ under light condition.

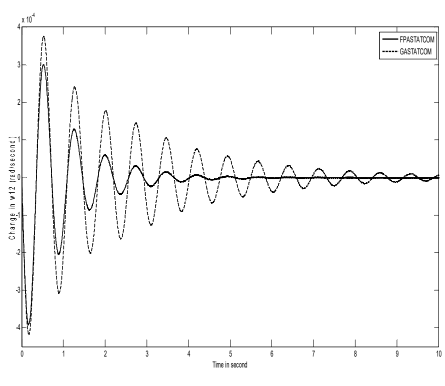

Fig. 9: Change of $\Delta\omega_{12}$ under heavy condition.

5.3 Response under Heavy Load Conditions

Figure 9 and Figure 10, show the system response under heavy loading conditions. These figures indicate the superiority of the FPASTATCOM in reducing the settling time and suppressing the power system oscillations. Moreover, the mean settling time of this oscillation is T_s =1.0 and 2.43 seconds for FPASTATCOM and GASTATCOM respectively. Also, the system without supplementary signal is suffered from sustained oscillations. Hence, the FPASTATCOM controller greatly improves the system stability and enhances the damping characteristics of the power system. Furthermore, the settling time of the proposed controller is smaller than that in, [35], [41].

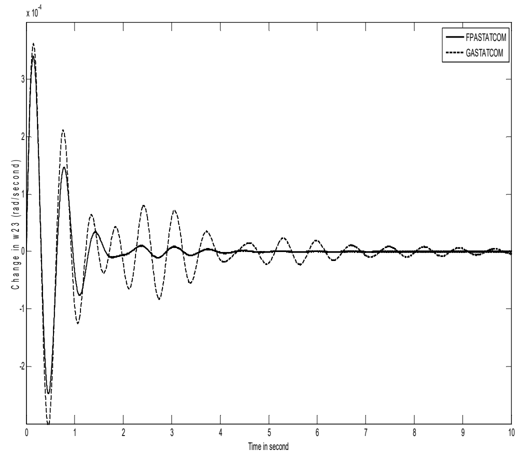

Fig. 10: Change of $\Delta\omega_{23}$ under heavy condition.

6 Conclusions

A new optimization algorithm known as FPA, for optimal setting of STATCOM parameters is proposed in this paper. The STATCOM parameters tuning problem is formulated as an optimization problem and the FPA algorithm is employed to seek optimal parameters. A time domain objective function involving the change of synchronous speed of the generator and DC voltage is proposed to alleviate power system oscillations and enhance system performance in terms of settling time and overshoots. Simulation results confirm the robustness and superiority of the proposed FPASTATCOM in providing good damping characteristics to system oscillations over a wide range of loading conditions compared with GASTATCOM

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APPENDIX

a) DC link parameters (p.u): V_{DC} =1.25; C_{DC} =1.0.
b) STATCOM ψ and c parameters have been recalculated, at each loading condition.
c) Parameters of FPA: Maximum number of iterations = 500, population size = 20, probability switch = 0.8.
d) The parameters of GA are as follows: Max generation=100; Population size=50; Crossover probabilities=0.75; Mutation probabilities =0.1.

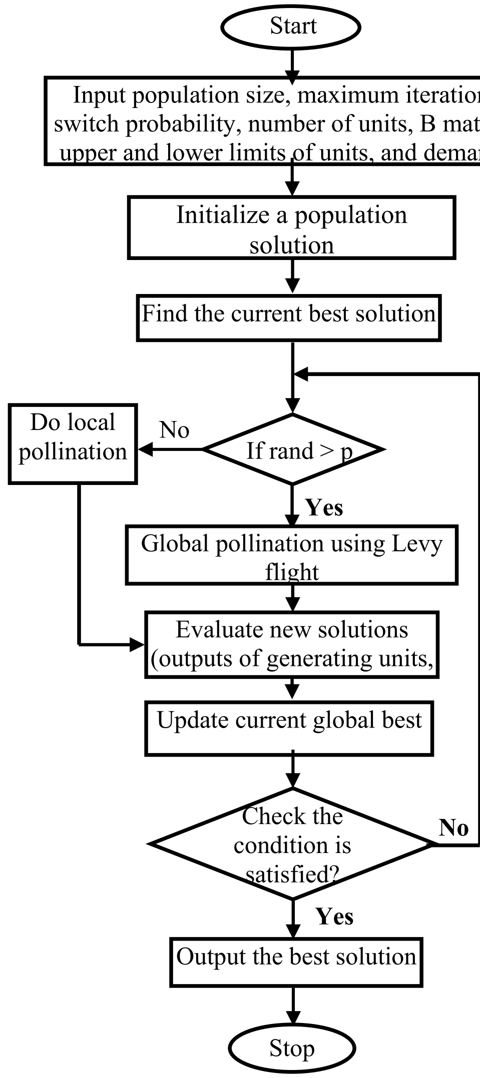

Fig. 4: Flowchart of FPA.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

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