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Allocation of Interline Power Flow Controller based Congestion Management in Deregulated Power System

Muhammad Safdar Sial[1,*] , Qinghua Fu[2] , Talles Vianna Brugni[3]

[1] *Department of Management Sciences, COMSATS University Islamabad (CUI), Islamabad 44000, Pakistan*

[2] *Department of Business Administration, Moutai Institute Zunyi City 563000, China*

[3] *Accounting Department, FUCAPE Business School, Av. Fernando Ferrari, 1358, Boa Vista, Vitória–ES 29075-505, Brazilf Management Sciences, COMSATS University Islamabad (CUI), Islamabad 44000, Pakistan*

Highlights

- Optimal allocation of IPFC in the power system to achieve appropriate structure for congestion management
- Modeling IPFC using new injecting power in power system
- Considering power losses and voltage profile improvement beside the main objective function
- Defining multi-objective factors, including cost and system factors
- Using upgraded SWSO algorithm to find the global best location

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Abstract

The present paper provides an optimal location of the Interline Power Flow Controller (IPFC) method in the power system using the Sperm Whales Swarm Optimization (SWSO) algorithm. The main aim of the IPFC's optimal location is to achieve an appropriate structure for congestion management in restructured power systems. The IPFC model changes the power flow by injecting power into the system. One of the most important issues to reduce power losses and improving the voltage profile, which leads to a reduction in the generation and congestion costs, is determining the appropriate location for installing IPFC. Therefore, an objective function is defined, including the stated parameter, minimizing the generation cost, congestion costs, power losses, and improving the voltage profile. Using the upgraded SWSO algorithm, a new approach to the optimal location of IPFC is presented. For validation, the proposed method has been implemented on the IEEE 14 bus restructured power system. By examining the obtained results, the performance of the proposed algorithm is better than the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms. It causes a further reduction in the generation cost, congestion costs, power losses, and improving voltage profile. Therefore, it is suggested that the proposed method be applied to the actual world restructured power system.

1. Introduction

With increased energy demand and occurs faults in transmission lines, the transmission losses are increased. Therefore, the temperature of the lines will rise, causing transmission congestion at this time [1]. One of the most critical challenges for ISO is to provide an appropriate method for managing congestion in power systems to provide security and increase the reliability of power systems. In improper congestion management, problems in the electricity market and increased marginal prices are created. The congestion management strategy minimizes transmission line congestion and the total active power cost and power losses [2]. Hence, several methods have been proposed to solve the mentioned problems: 1-the establishment of new transmission lines 2- the operation of Flexible AC Transmission System (FACTS) devices. The establishment of new transmission lines because of high costs and environmental issues is not a suitable method [1]. By installing the Flexible AC Transmission System (FACTS) devices on the power system, the power flow improves, leading to line congestion management [3]. In recent years, one of the most important issues in the

* Corresponding Author: Muhammad Safdar Sial
Email: safdarsial@comsats.edu.pk

performance of the restructured power system is to utilize FACTs in proper condition [4]. Fact sheet utilization improves power flow conditions and congestion management [5-6]. The researchers seek to find a suitable method for optimal placement of FACTs devices. IPFC is one of the most utilizable and suited equipments for achieving appropriate congestion management through the facts devices. IPFC has power control capabilities through power injections to the bus. The advantages of IPFC include increasing the loading of transmission lines, regulating and managing the load flow, and compensation for reactive power, which leads to improved voltage profile and increased dynamic and transient network stability. IPFC is a serial-series controller, and in multi-transmission lines, it is capable of reactive power compensation using Voltage Sourced Switching Converters (VSCs) connected in series to the transmission lines. Hence, this paper applies the IPFC model to the power system to achieve these mentioned ideas. The optimal location of the FACTs is determined using linear and nonlinear programming [7], as well as a variety of algorithms such as evolutionary programming and differential evolution [8], Particle Swarm Optimization (PSO) [9], Genetic Algorithms (GA) [10], Artificial Neural Networks (ANN) [11], and Evolution Methodologies [12]. It should be noted that among all algorithms, heuristic algorithms are suitable for the optimal location. Still, on the other hand, because these algorithms are inspired by human behavior and inherent features, the time of implementation is long. The algorithms described above have some disadvantages in addition to the advantages. One of these disadvantages is getting into a locally optimal point. This paper introduces a new algorithm to solve this problem, inspired by sperm whales' behavior. The name of the new algorithm is Sperm Whales. It also has the following advantages: Sufficient time to compute the complex issues, high-speed convergence, and finding the global optimal point. IPFC optimal placement with congestion management is implemented on the IEEE 14 bus systems to analyze the proposed algorithm's performance. For more details of the IEEE 14 bus systems, refer to Ref. [12]. Finally, the obtained results from the system simulation represent the superior performance of the proposed algorithm. It can be stated that using optimal load flow through the proposed method, the cost of power generation and losses by considering the constraints and congestions are minimized. As a result, the proposed technique can be used in a real system.

2. The Mathematical Model of the Proposed Method

In the real power system, in the event of various faults such as the removal of transmission lines due to natural circumstances, the heat rates of the transmission lines are increased. As a result, the loading congestion gets over the limit of the line. Even if the line limits are increased, the nodal prices in the energy market will be increased. Factors that caused to raise the nodal prices include:

1. Swelling the production costs.

$$C = \sum_{i=1}^{N_g} C_{gi} \, . P_{gi} \tag{1}$$

In this equation, the overall production cost and the production cost in bus $i - th$ are represented by C and Cgi, respectively. Also, the power of the $i - th$ bus is denoted by Pgi.

1. Swelling loss of the transmission lines
2. Swelling congestion costs

The congestion cost (CC**)** is calculated by Eq (2):

$$TCC = \sum_{ij}^{N_i} \Delta\lambda_{ij} P_{ij} \tag{2}$$

Where,:

$$\Delta\lambda_{ij} = \lambda_i - \lambda_j \tag{3}$$

In this equation, the bordering local cost in the bus $i - th$ or bus $j - th$ is represented by λi (or λj); also, the power flow from bus i to bus j is represented by P_{ij}.

The standard IEEE 14 bus system structure is shown in Fig. 1 to examine the congestion management in the power system. Refer to Ref. [13] for more data. The congestion is created when the heat of the transmission lines exceeds the specified range. Convergence management lines in restructured systems are controlled by independent system operation (ISO). In a recent study, researchers have introduced new Flexible AC Transmission System (FACTS) devices to manage congestion in power systems [14].

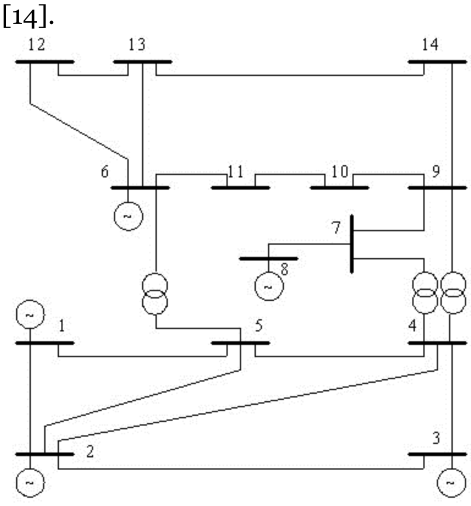

Fig. 1. Structure of IEEE 14 bus standard test case.

The main purpose of using FACTS devices is to reduce the congestion of the lines through the injection of power into lines and change the system's power flow [15]. Interline Power Flow Controller (IPFC) is one of the most suitable FACTS devices to balance line congestion. IPFC controller includes two serial-series DC-link converters that can inject active and reactive power into the power system. The structure of the IPFC controller and its power injection model is depicted in Fig. 2, which is derived from Ref. [16]. The IPFC controller connects to the three busses of the power system in series state (i, j) and (j, k) and shown in Fig. 3, which changes the bus voltages by power injection, the power injected into the three buses in terms of the bus voltage $(Vse_{in} = Vse_{in} < \Theta se_{in})$ is calculated through the Eqs in the following [1].

$$P_{inj,n} = Re\left\{V_i\begin{bmatrix}(y'_{ij} + y_{i1}^{shunt})Vse_{ij} \\ +(y'_{ik} + y_{i2}^{shunt})Vse_{ik}\end{bmatrix}^*\right\} \quad (4)$$

$$Q_{inj,n} = Im\left\{V_i\begin{bmatrix}(y'_{ij} + y_{i1}^{shunt})Vse_{ij} \\ +(y'_{ik} + y_{i2}^{shunt})Vse_{ik}\end{bmatrix}^*\right\} \quad (5)$$

$$P_{inj,n} = Re\,\{V_n[(-y'_{in})Vse_{in}]^*\} \quad (6)$$

$$Q_{inj,n} = Im\,\{V_n[(-y'_{in})Vse_{in}]^*\} \quad (7)$$

Where n=j, k

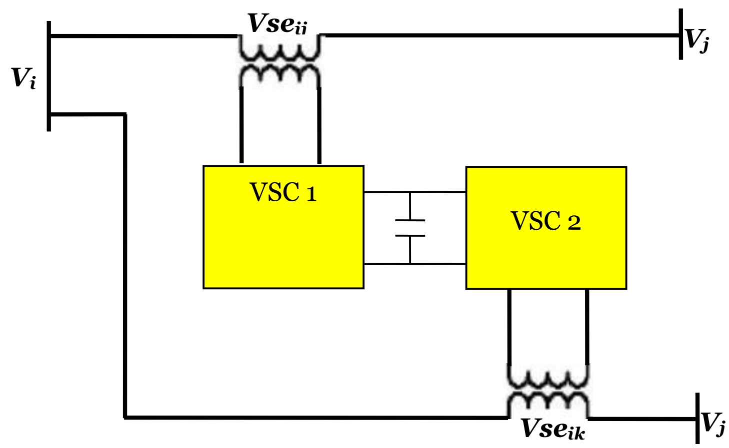

Fig. 2. IPFC Schematic diagram

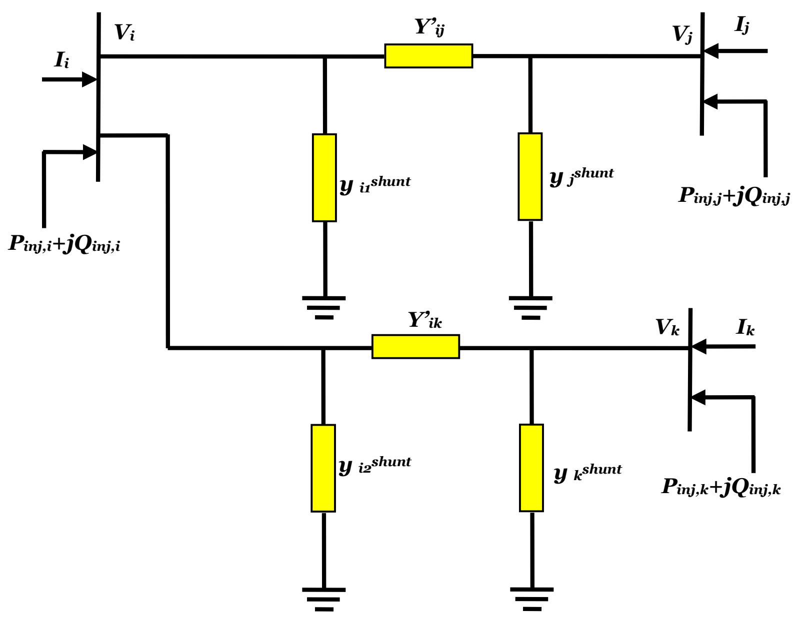

Fig. 3. The power injection model of IPFC.

The optimal placement of IPFC aims to determine the most suitable location for installing IPFC and determine the optimal values for its parameters. Therefore, the objective function must be defined so that both objects are achieved at the same time. The optimal location of IPFC in the real system is based on the cost function, taking into account voltage constraints, minimizing production costs, losses cost, and congestion cost. In Eq. (8), the cost function is formulated with the considering mentioned objective.

$$f = a_1 \sum_{i=2}^{N_g} (1.05 - V_i) - (0.95 - V_i) + C + a_2.loss + a_3 .TCC \quad (8)$$

According to the numerical result in the preceding equation, the constant coefficients denoted by a_1, a_2, and a_3, are chosen to 36000, 900, and 16, respectively. Also, $i-th$ bus voltage is shown with Vi. Using an intelligent algorithm aims to raise the loading capacity of transmission lines and do an optimal power flow with reactive compensation power, which is done by power injection through IPFC. Hence, in this paper, an upgraded Sperm Whales Swarm algorithm is proposed, called the sperm whales swarm optimization (SWSO) algorithm. The proposed algorithm is created by benchmarking the whale sperm movement type with defection rates to inspect nitrify behavior, evaluate the problem size of the part of prey, and the distance between them [17].

3. Structure of SWSO Algorithm

The main purpose of the optimization problem is similar to the whales' collective movement to achieve a common goal. Hence, modeling their movement as a new algorithm is suitable for optimization problems [18]. The algorithm studied in this paper, which modes based on the whale's behavior, is called the sperm whales swarm optimization (SWSO) algorithm. Each whale group consists of 50 individuals, and one of the whales is chosen as the group's leader, with another member following him. The leaders of all groups are also in contact together, which is shown in Fig. 4. Based on the closest whale to the target, the leader of the group is selected. There is a possibility of changing the subgroup leader and the main group during the whales' grouping movement.

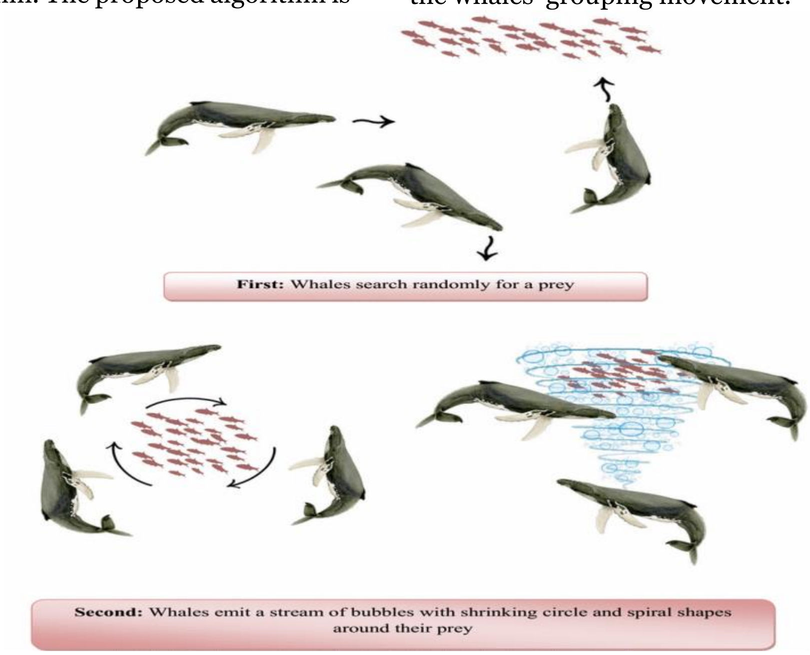

Fig. 4. The three group whales.

The steps to implement the SWSO algorithm are as follows:

Step 1: Many sperm whales are randomly created in each group (SW), SW is in the range of $1 \leq sw \leq 10$.

Step 2: The fitness is selected according to the position of each sperm for SW the population

Step 3: The current position of each particle is compared with the best previous position of all particles and their necessary replacement in n particles, and the best position of the particle is selected.

$$If\ F(P_i^n) > pbest_i^n \Rightarrow \begin{cases} pbest_i^n = F(P_i^n) \\ \vec{x}pbest0_i^n = \vec{x}_i^t(t) \end{cases} \quad (9)$$

Step 4: The current position of each particle is compared with the best previous position of all particles and location in n particles, and the best position of the particle is selected.

$$If\ F(P_i^n) > gbest^n \Rightarrow \begin{cases} gbest^n = F(P_i^n) \\ \vec{x}gbest^n = \vec{x}_i^t(t) \end{cases} \quad (10)$$

Step 5: The current position of each particle is compared with the best previous position of all particles and the necessary location in n particles, and the best position of the particle is selected.

$$If\ F(P_i^n) > hbest \Rightarrow \begin{cases} hbest = F(P_i^n) \\ \vec{x}hbest = \vec{x}_i^t(t) \end{cases} \tag{11}$$

Step 6: For each particle in the n population, the velocity vector is computed using Eq (12).

$$v_{id}(t+1) = w.v_{id}(t) + c_1.rand(g\_best_{\ id} - x_{id}) + c_2.rand(h\_best_{\ id} - x_{id}) \tag{12}$$

h_best is the best answer obtained from the comparison among the g_best and selected the smallest of them.

Step 7: the new position of each particle in the n population is calculated from Eq. (13).

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \tag{13}$$

Step 8: If convergence is reached, it stops; otherwise, it returns to step 2.

In Eq. (12), inertia weight is represented by w. Also, the training factor c_1 is and c_2, respectively, and are equal to 2. The degree of convergence is proportional to w and based on it is defined. In the evolution of the population process, the linear trend is down from 0.4 to 0.9. Initially, the larger this value is, the more appropriate it achieves the best answers. On the other hand, small values w increase the convergence rate and obtain better results for convergence. This downward trend is defined using Eq (14).

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \times iter \tag{14}$$

Two groups ($n = 2$) are assumed in the proposed algorithm for this study.

The performance of the suggested method can be examined using a variety of mathematical functions. In this paper, the JINC function is proposed to evaluate the performance of the proposed algorithm. The ***jinc*** function has a kind of sample Fourier transform. For large values of X, $\boldsymbol{jinc}(t)$ is done a damped, shifted cosine. Specifically, it is defined as follows:

$$jinc\ (x) \approx cos\left(|x| - \frac{3\pi}{4}\right)\sqrt{\frac{2}{\pi|t|^3}} \tag{15}$$

The three-dimensional structure of the JINC function is depicted in Fig. 5. As seen, this function has many local points and also has only one global point. This function is embedded in the proposed algorithm, and then the global maximum point is obtained. In Table 1, the results of the implementation of 10 independent runs of the program are listed using the proposed algorithm and the optimization of the JINC function with the assumption $f(x) = 1$.

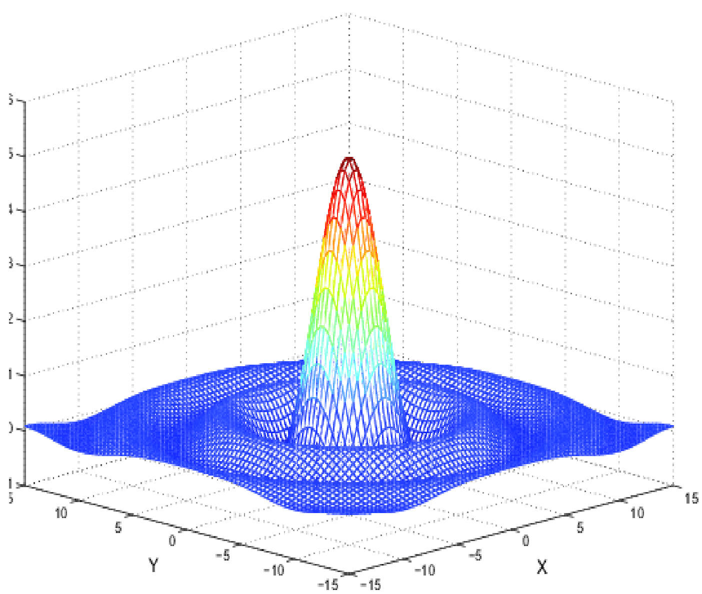

Fig. 5. The three-dimensional JINC function.

Table 1. Results of 10 independent run by SWSO algorithm.

Implementation	SWSO algorithms	error
1	0.99975	0.00025
2	0.99998	0.00002
3	0.99980	0.0002
4	0.99875	0.00125

5	0.99998	0.00002
6	0.99995	0.00005
7	0.99990	0.00010
8	0.99988	0.00012
9	0.99994	0.00006
10	0.99995	0.00005
Average	0.99976	0.00195
Average time	0.1393	
The best results	0.99998	

By examining the results given in Table 1, it can be stated that the best answer given by the JINC function is 0. 99998. The mean value of best F (x, y) in 10 iterations is 0.99976, which is achieved on average 0.1393 seconds. 0.99875 is the highest deviation. The convergence of two independent groups of SWSO algorithms is depicted in Fig. 6.

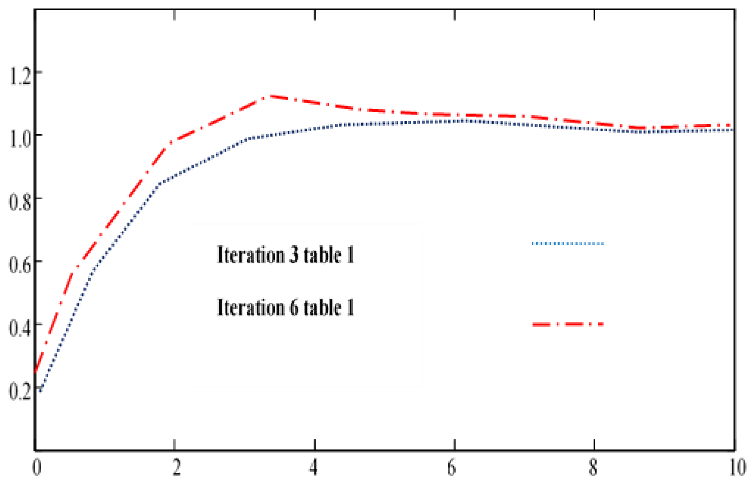

Fig. 6. Convergence of two independent groups of SWSO algorithms.

The SWSO algorithm is proposed to confront the issue of lines congestion (density management).

4. Numerical results

In this paper, the new SWSO algorithm is proposed to manage congestion through appropriate power flow. The total structure of the proposed test case is 14 buses, 16 lines, two synchronous generators, and three synchronous condensers, which is depicted in Fig. 1. Refer to Ref. [13] for more information. In this study, using the SWSO algorithm, the optimal location of IPFC is determined. To increase system efficiency and manage congestion, determining the optimal amount of IPFC parameters is an essential issue along with optimal IPFC location. Therefore, it's essential to use the appropriate programming to implement both of the mentioned goals, plotted in Fig. 7. The first three bits refer to the IPFC location in the coding, and the next three bits represent the IPFC parameter.

bus_i	bus_y	bus_u	Vse_y	Vse_u	δse_y	δse_u

Fig. 7. Construction of each population.

The implementation of the proposed algorithm flowchart for managing congestion is shown in Fig. 8. The objective function is described in Eq. (8), in which Eqs. (16) and (17) of the constraints of the objective function are also expressed.

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad , \quad V_i^{min} \leq V_i \leq V_i^{max} \tag{16}$$

$$V_{se1}^{min} \leq V_{se1} \leq V_{se1}^{max} \quad , \quad \delta_{se1}^{min} \leq \delta_{se1} \leq \delta_{se1}^{max}$$

$$V_{se2}^{min} \leq V_{se2} \leq V_{se2}^{max} \quad , \quad \delta_{se2}^{min} \leq \delta_{se2} \leq \delta_{se2}^{max} \tag{17}$$

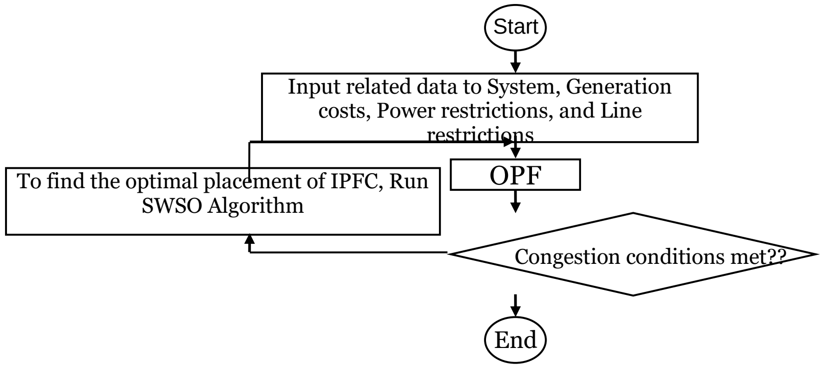

Fig. 8. The new congestion management flowchart.

As shown in Fig. 9, the SWSO algorithm reaches the lowest value and convergence in 8 iterations. The final results are shown in Table 2.

Table 2. IPFC Parameters.

bus_i	bus_y	bus_u	Vse_y	Vse_u	δse_y	δse_u
3	3-4	3-2	0.24	0.18	43	68

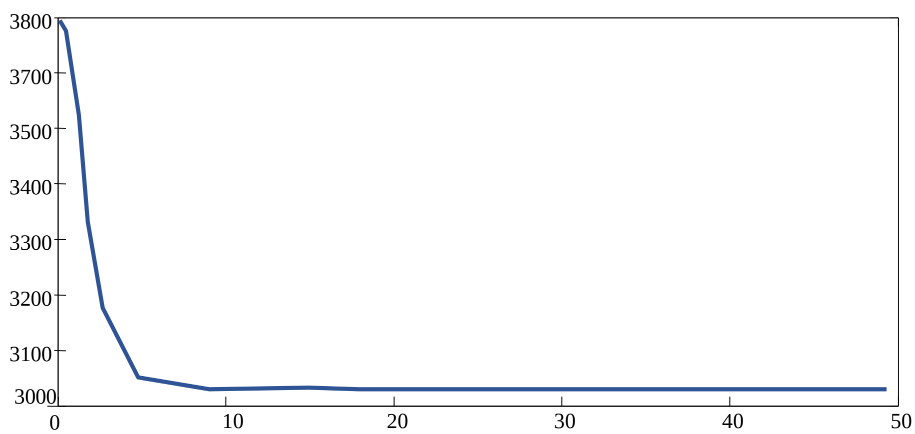

Fig. 9. The process of convergence SWSO algorithm.

In order to evaluate the performance of the proposed method in comparison with other methods, Partial Swarm Optimization (PSO) [9], Genetic Algorithm (GA) [10] was implemented on the 14-bus system, and the results in two cases are as follows. In Table 3, the result of this modeling is given.

Case1: Limitations on transmission lines are discarded.

Case2: 80 MW restrictions are considered in transmission lines.

In order to measure the suggested technique's resistance to load uncertainty, the load was changed by 20%, as illustrated in Fig. 10. If the IPFC is installed at LINES 3-2 and 3-4, the congestion cost is reduced to an acceptable level. The overall cost is raised due to the use of IPFC, losses, production, and congestion cost.

Table 3. The numerical results of the implementation of case 1 and case 2.

	Case1	**Case2**		
	Without IPFC	**With IPFC location through GA algorithm**	**With IPFC location through PSO algorithm**	**With IPFC location through SWSO algorithm**

Overall Power (MW)	263.535	263.26	257.44	252.65
Overall Costs ($/h)	7981.1	7975.6	7675.44	7598.35
Losses (MW)	8.446	8.251	6.55	5.13
Congestion costs ($/h)	524	338	325	305
Power flow in line 3-2 (MW)	116.434	78.49	77.331	73.238
Power flow in line 3-4 (MW)	73.43	73.28	69.32	70.535
target function	29851	29212	28993	27998

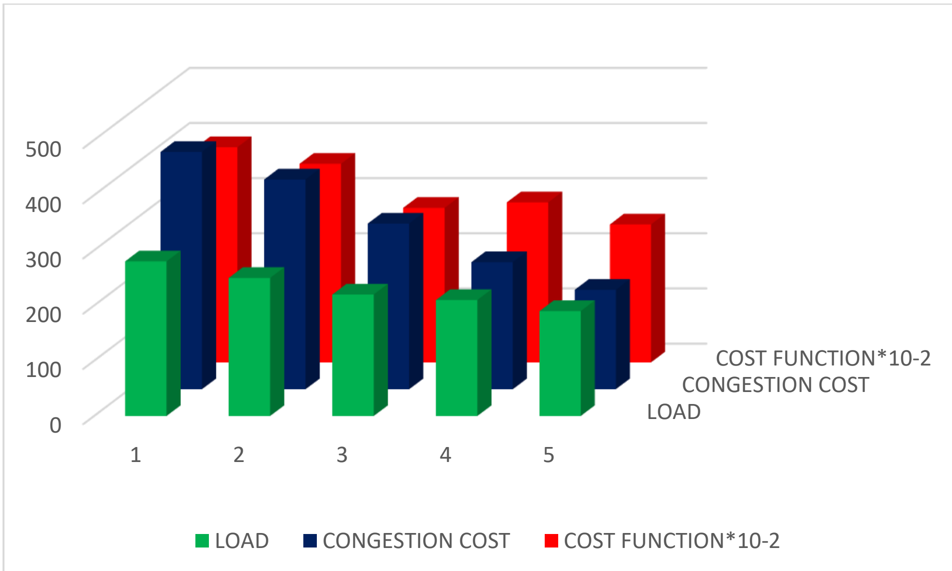

Fig. 10. Load uncertainty investigation on the purposed method.

5. Conclusion

In this paper, IPFC is used to manage the congestion and increase the system performance. On the other hand, the optimal location and parameter change have been investigated for achieving maximum returns using the whale algorithm. The newly upgraded algorithm based on SWSO has been effectively applied to solve congestion management by utilizing IPFC. In the proposed algorithm, the objective function is the production cost, power losses, and congestion costs. In order to evaluate the performance of the proposed method, this method was implemented on the IEEE 14 test system, and the results were compared with the obtained results from modeling this system using GA and PSO-based methods. By analyzing the results, it was found that the proposed method has a better performance in minimizing cost and managing congestion than other methods. Finally, with the optimal location of IPFC and determining the appropriate parameters' values of IPFC, the capacity of the transmission lines is increased, and the overall cost is reduced.

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