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Research Article

Power System Performance Enhancement with FACTS Devices

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Abstract

The power system network is growing in size day by day with the exponential growth in demand. The optimal operation of power system gains much more attention of worldwide researchers which necessitates sophisticated methodology and technique. Even though many optimization methods are propsed already, the optimality is still doubtful. To address this challenge, an innovative improved wind driven optimization algorithm (I-WDO) is proposed in this work. With the optimal integration of Flexible AC Transmission System (FACTS) devices much more benefits are also extracted. The system performance is evaluated in terms of fuel cost and power transmission losses. The obtained results with the proposed I-WDO are compared with that of various evolutionary approaches. On observing the results, it can be concluded that the fuel costs and losses are minimum with the proposed I-WDO algorithm and also with the incorporation of FACTS devices.

Keywords: Optimal Power Flow (OPF), Flexible AC Transmission System (FACTS), Unified Power Flow Controller (UPFC), Improved wind driven optimization algorithm (I-WDO), Active power loss, Transmission loss.

1. Introduction

Today most of the power in the world is produced by the thermal plants only. The fuel for the generation of power in a thermal plant is coal. Though the coal fuel resources are going to exhaust, this evolves as a main source for electric generation. The second main problem with the coal fired plants is, the huge cost involved in procuring, processing and its utilization. Therefore, it is a responsibility of any electric engineer to reduce the cost of fuel. So that, electric power can be delivered to end consumer with utmost minimum cost.

Optimal power flow (OPF) solution is to find the operating state of the variables by properly tuning them such that the overall cost can be minimized. In OPF the fuel cost minimization only is the main objective. But, in practice there are 10 to 15 percent of sending end power is contributed towards the transmission losses. By properly tuning the electric parameters, these losses also can be minimized to certain extent. Mathematically, the loss function also can be included in the objective function. Which can be considered as multi objective problem.

The transmission lines are used to transfer the power from generating location to the end consumers. Currently the main issue with the transmission system is that they are not utilizing up to their maximum capacity level. After transmitting a certain amount of the power, still it has capacity to transmit without violating the operational constraints. In other terms it also known as loadability. The transmission system loadability need to be improved for economic utilization.

During solving the OPF problem, the loadability enhancement also can be considered. Without violating the system and operational constraints the loadabiity enhancement can be obtained. This reduces the cost of installing new transmission system.

FACTS devices are well known for their precise operation for maintaining security of the system. If proper FACTS device is selected according to the requirement and located optimally the benefits achieved will be unimaginable.

To complete all the aforementioned tasks, a normal conventional algorithms are not at all suitable. Therefore, a novel hybrid heuristic algorithms need to be proposed to take care of all non-linearities in a system.

The OPF problem is a very important analysis that's need to be carried out for economic, secure and satisfactory operation of power system. It involves the regulating of control parameters in the prescribed limits. A numerous work is carried out for suggesting its optimal operation. At the same time with the development of power electronic devices FACTS devises found their use in various power system applications. Later with the integration of renewable energy sources also the operation of power system becomes still more complicated for handling their uncertain generation. The same OPF problem can be extended further to distribution system in case of installation of Distributed Generation.

Covering all these concepts a few of the literature are presented in the subsequent sections. The authors of [1] studied various challenges while solving OPF problem. They emphasizes Cockroach Swarm Optimization (CSO) algorithm for solving OPF problem on IEEE 9 bus system. In [2], the authors done a comprehensive literature and tried to solve OPF problem, while optimally placing various FACTS devices. The authors of [3] installed various SVC FATCS device in optimal locations and done the analysis for loss minimization, voltage profile enhancement and at the same time reduction of fluctuations on standard IEEE 9 and IEEE 30 bus system.

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Loadabiity is one of the concept arises to make use of available transmission line to its maximum level without violating system and operational constraints. This reduces the cost of new installation of transmission lines. The authors of [4] suggested a new technology for solving OPF problem by suggesting the incorporation of power flow routers. Congestion is a problem that every power system engineer need to focus. The poor planning may lead to transmission line congestion. The authors of [5] utilized multiple FACTS devices to elevate the loadability of the system at the same time mitigating the congestion of power system. They have make use of SVC and STATCOM on IEEE-14 bus system and the performance has been studied. In reference [6] also the authors have placed SVC optimally to minimize the system loss while enhancing the voltage stability. The authors have make use of Genetic algorithm for solving the identified problem and performed the analysis on standard IEEE 6 bus system.

The authors of [7] carried out their work to nullify the line overloads by handling re economic dispatch online without violating security constraints. It also studies in case of over loads by online economic re-dispatch under emergency situation also. In [8], the authors carried out their work in deregulation system environment. Here also the authors strives for mitigating the overloading by reducing the contingency case. They have make use of Interline power flow controller as FACTS device and Gravitational Search Algorithm for obtaining the desired objective. The authors of [9] presented a novel methodology for handling renewable energy integration to the power system. Their main emphasis is on solving the OPF problem as usually to minimize the fuel cost, reducing the loss and at the same time to handle the adverse environmental effects raised by the fossil fuel plants.

In [10], the authors develops an intelligent power flow controller by making use of grasshopper algorithm for optimization of dynamic response. The obtained results are compared with that of particle swarm optimization algorithm. The authors of [11] proposes Augmented Lagrangian Based Alternating Direct Inexact Newton (ALADIN) to solving AC Optimal power flow problem. In [12, 15], the authors obtains optimal location of Interline power flow controller to study the dynamic performance using OPF problem. The authors also make use of BAT algorithm to obtain the desired objectives.

In the present work, a novel heuristic algorithm is proposed, the OPF problem is solved while considering cost minimization, loss minimization and also enhancement of loadability. The FACTS devices also located optimally to solve the above said objectives and obtained satisfactory results.

1.1. Optimal Power flow solution

The main concept of Optimal Power Flow solution is to find the final optimal operating state of the power system by properly selecting the settings of the control variables at the same time satisfying the system equality and Inequality constraints to achieve the economic operation. The generators are allocated load and losses economically. Solving the OPF is problem is highly nonlinear. So a sophisticated tool is indeed necessary to obtain the optimal operating point of the system.

1.2. Mathematical modelling of OPF

The solution of OPF problem is to obtain the steady state operating point of the system to achieve the optimum cost, while satisfying the equality and in-equality constraints.

Mathematically, it can be formulated as:
Minimize

$$F(x,u) \tag{1}$$

Subjected to

$$g(x,u)=0 \tag{2}$$

$$h(x,u)\leq 0 \tag{3}$$

Where, the functions F is the objective function, g is set of equality and h is set of inequality constraints. All these functions are expressed in terms of x and u. x represents the vector of dependent variables and u represents the vector of independent variables. The dependent variables include Slack power generation, Voltages at all load buses, Reactive power generations of generators and MVA loadings of the transmission lines. The independent vector includes the active power generation and voltages at the generator buses except at the slack bus, tap settings of tap changing transformers and shunt VAR compensation.

The objective function considered here is to minimize the fuel cost,

Minimize

$$F_T=\sum_{i=1}^{NG}F_i\,(P_{Gi}) \quad \text{in Rs/hr} \tag{4}$$

F_T is the total fuel cost expressed in Rs/hr, which is the sum of all the individual generator's fuel cost and NG is the number of available generators. Fi (PGi) is the fuel cost of ith generator to generate PGi power in MWs and is expressed as

$$F_i(P_{Gi})=a_i\times P_{Gi}^2+b_i\times P_{Gi}+c_i \quad \text{in Rs/hr} \tag{5}$$

Where, $a_i, b_i and c_i$ are the cost coefficients of the generators.

Subjected to,

(a). Equality Constraints:

(i). Active Power balance Equation: The total active power generation which is the sum of all the individual generations must be equal to demand and transmission losses.

$$\sum_{i=1}^{NG}|V_i||V_j||Y_{ij}|Cos(\delta_i-\delta_j-\theta_{ij})=P_D+P_L \tag{6}$$

Where, $|V_i| and |V_j|$ are the voltage magnitudes, $\delta_i and \delta_j$ are the voltage angles at buses i and j respectively and θ_{ij} is the bus admittance matrix angle. P_D is the electrical power demand. P_L is the electrical transmission losses.

(ii). Reactive Power balance Equation: The sum of reactive power generation and shunt reactive compensation must be equal to the sum of the reactive demand and reactive power losses.

$$\sum_{i=1}^{NG}|V_i||V_j||Y_{ij}|Sin(\delta_i-\delta_j-\theta_{ij})=Q_D+Q_L \tag{7}$$

Where, Q_D and Q_L are the reactive power load and reactive losses in a system.

(b). In Equality Constraints:

The real, reactive powers and voltage magnitudes at the generator buses, line flows, voltages at all load buses, tap settings of tap changing transformers and shunt reactive powers injected must be with in their specified minimum and maximum limits.

$$P_{Gi}^{Min} \leq P_{Gi} \leq P_{Gi}^{Max} \forall i \in NG \quad (8)$$

$$Q_{Gi}^{Min} \leq Q_{Gi} \leq Q_{Gi}^{Max} \forall i \in NG \quad (9)$$

$$V_{Gi}^{Min} \leq V_{Gi} \leq V_{Gi}^{Max} \forall i \in NG \quad (10)$$

$$S_{li} \leq S_{li}^{Max} \forall i \in nl \quad (11)$$

$$V_{i}^{Min} \leq V_{i} \leq V_{i}^{Max} \forall i \in LB \quad (12)$$

$$T_{i}^{Min} \leq T_{i} \leq T_{i}^{Max} \forall i \in NT \quad (13)$$

$$Q_{shi}^{Min} \leq Q_{shi} \leq Q_{shi}^{Max} \forall i \in NC \quad (14)$$

2. Proposed Improved Wind Driven Optimization algorithm

Wind Driven Optimization (WDO) algorithm is developed by inspiring from the natural behavior of the moment of air particles in the atmosphere which arises due to the non-uniform distribution of pressure. [13, 16]. WDO is proposed depending on multi-dimensional and multi modal based global optimization algorithm. The trajectory of each air parcels is governed by the Newton's second law. The moment of air parcels is directed by four forces. The frictional forces arises due to the neighboring particles, the force of earth gravity, which draws the air parcels to center of search space, the force exerted by pressure gradient and forces due to Coriolis. The position and the velocity of every air particle is updated by making use of equations 15 and 16.

$$V_{t+1} = (1-\alpha)V_t - gx_t + RT\left|\frac{1}{r} - 1\right|(x_{opt} - x_t) + \frac{cu_t^{otherdim}}{r} \quad (15)$$

$$x_{t+1} = x_t + V_{t+1} \quad (16)$$

In this thesis, an I-WDO is proposed to obtain the convergence much faster. A novel factor known as wind factor (w_f) is introduced to obtain much better satisfactory results. The value of w_f is tested on many standard functions and its value is concluded to be in the range of 0 to 2. With the development of wind factor the velocity equation 15 is modified as equation 17.

$$V_{t+1} = (1-\alpha)V_t - gx_t + RT\left|\frac{1}{r} - 1\right|(x_{opt} - w_f \times x_t) + \frac{cu_t^{otherdim}}{r} \quad (17)$$

The position update is done according to the equation 15. The generalize step by step procedure to solve the problem using I-WDO is described in the following steps.

The implementation of I-WDO involves the following steps.

Step 1: Initialize I-WDO algorithm and problem specific parameters.
Step 2: Define the Objective function for the considered problem.
Step 3: start with initial population i.e. position and velocity randomly with in the search space.
Step 4: Obtain the fitness value of each air parcel.
Step 5: The current velocity of the particle should be updated using equation 17.
Step 6: Check if there is any violation in velocity limit.
Step 7: The current position of air parcel should be updated using equation 16.
Step 8: Check if there is any violation of position limit.
Step 9: Increase the iteration count and check for the maximum iteration limit has been reached.
Step 10: Repeat the steps from 4 to 9 until the convergence condition is satisfies.
To validate the accuracy of the proposed I-WDO algorithm, it was used to solve for load flow solution using FDLF approach.

3. Modelling of Unified Power Flow Controller (UPFC)

The UPFC mainly consists of two converters, which are connected back to back with a DC link. One converter connects to the transmission line through a series transformer, which regulates the voltage injected into the line and the second converter is connected through shunt transformer. The purpose of second converter is to provide the active power requirement of first converter through the DC link. The implementation of UPFC in transmission system has been shown in Fig 1.

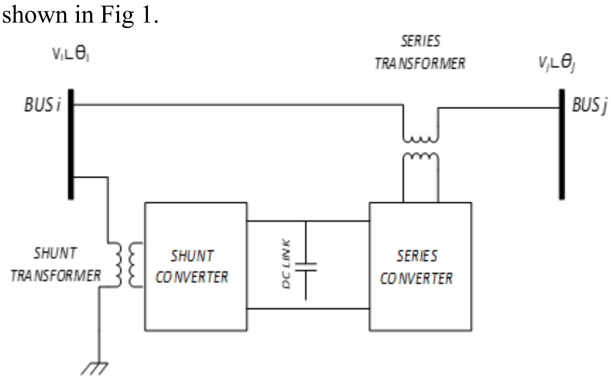

Fig 1. Circuit Diagram of UPFC.

The present work makes use of a power injection model of UPFC, where the equivalent circuit of UPFC has been represented by a two voltage source model [14, 17]. V_i is the voltage at bus i with voltage angle Θi and holds the same for bus j also.

Where $\overline{V_S}$is the series voltage source and can be given as:

$$\overline{V_S} = r\overline{V_i}e^{j\gamma} \quad (18)$$

Its magnitude and phase angle can be controlled with r and γparameters. The operating limits of r and $\gamma$are specified as$0 < r < r^{max}$.

As the series voltage source does the main functionality, it is indeed necessary to model series voltage source. The Norton equivalent to the series voltage source can be represented as below.

The current source value is given as:

$$\overline{I_S} = -j(\frac{\overline{V_S}}{X_S}) \quad (19)$$

Where $1/X_s = b_s$

The apparent power injected in to the i[th] bus:

$$\overline{S_{iS}} = \overline{V_i} * (-\overline{I_S})^* \quad (20)$$

Similarly, the power injected into j[th] bus:

$$\overline{S}_{jS} = \overline{V}_j * (\overline{I}_S)^* \quad (21)$$

On solving above equations the real and reactive power injections can be obtained as:

$$P_{iS} = -rb_sV_i^2 \sin\gamma \quad (22)$$

$$Q_{iS} = -rb_sV_i^2 \cos\gamma \quad (23)$$

$$P_{jS} = V_iV_jb_sr \sin(\theta_{ij} + \gamma) \quad (24)$$

$$Q_{jS} = V_iV_jb_sr \cos(\theta_{ij} + \gamma) \quad (25)$$

The shunt converter used to provide the active power which is injected into the transmission line through series converter. When UPFC is a lossless

$$P_{ShuntConv} = P_{SeriesConv} \quad (26)$$

$$S_{Series} = \overline{V_S} * \overline{I_{ij}}^* \quad (27)$$

On solving

$$P_{Series} = b_srV_iV_j \sin(\theta_{ij} + \gamma) - b_srV_i^2 \sin\gamma$$

$$Q_{Series} = -b_srV_iV_j \cos(\theta_{ij} + \gamma) + b_srV_i^2 \cos\gamma + r^2b_sV_i^2$$

$$Where\ \theta_{ij} = (\theta_i - \theta_j) \quad (28)$$

The total UPFC power injected at the two buses i and j can be obtained by merging shunt and series connected voltage source models.

$$\begin{aligned} P_{i,U} &= -b_srV_iV_j \sin(\theta_{ij} + \gamma) \\ Q_{i,U} &= -b_srV_i^2 \cos\gamma \\ P_{j,U} &= b_srV_iV_j \sin(\theta_{ij} + \gamma) \\ Q_{j,U} &= b_srV_iV_j \cos(\theta_{ij} + \gamma) \end{aligned} \quad (29)$$

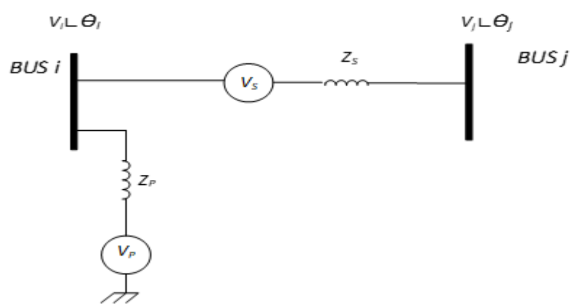

Fig 2. Two voltage source model of UPFC.

4. Optimal location of UPFC device

In an interconnected complex power system, the flexible, reliable and economic operation can be obtained by installing UPFC device in a proper location. While installing it needs to keep in mind that, UPFC should not be located at the generator buses, in the shunt compensated buses and the lines where tap changing transformers are connected. To find the optimal location of UPFC in the given network, a sensitive function (Fs) is considered. Fs is defined based on MVA calculation as shown in expression 30.

$$F_s = \sum_{i=1}^{nl} (S_i^{Max} - S_i^{Avb})^2 \quad (30)$$

F_s is calculated for different location of UPFC placement. The location at which F_s is minimum is said to be optimal location.

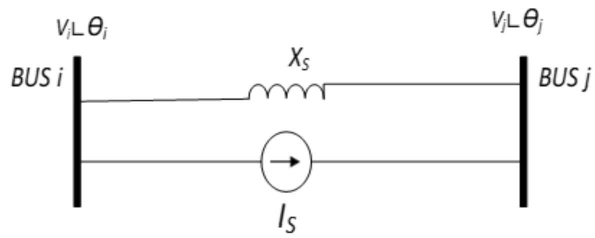

Fig 3. Norton equivalent of series voltage source of UPFC

5. Solution Methodology

The following is the step by step procedure adopted to solve the OPF problem with and without the presence of UPFC device.
Step 1: Find the optimum location of UPFC device such that the sensitive function is minimum.
Step 2: Solve the OPF problem with the help of I-WDO algorithm.
Step 3: Solve the OPF problem in the using I-WDO by incorporating UPFC device.

6. Results and Analysis

6.1. Case (i): Solution of OPF using I-WDO without incorporation of UPFC.

The OPF problem is solved using I-WDO algorithm for a standard IEEE 14 bus system. Which has one slack bus, 4 generator buses, 9 load buses and 20 transmission lines.

The single line diagram with line numbers is shown in Fig 4. The Table 1 shows the optimal power generations of various generators and transmission losses in an IEEE 14 bus system. From the obtained results it can be observed that, the power obtained are yields to the minimum cost of 767.97 \$/hr and the transmission losses are observed to be 4.62 MW.

Table 1. Results of OPF without UPFC

S.No	Bus No.	Active Power Generation (MW)	Cost (\$/hr)	Active Power Losses (MW)
1	1	93.74	767.97	4.62
2	2	75.65		
3	3	27.83		
4	6	45.03		
5	8	21.34		

6.2. Case (ii): Solution of OPF using I-WDO with incorporation of UPFC

In this case, the OPF problem is solved by incorporating UPFC device. For that purpose, it needs to identify the optimal location of UPFC in a given system in such a way to minimize sensitive function. The UPFC is located in all possible locations and the sensitive function is calculated. The minimum and maximum limits considered for the UPFC variables are: $0 \leq r \leq 0.09$, $1.25 \leq bs \leq 50$ and $0 \leq \gamma \leq 360o$ It is identified that when the UPFC is in line no.7, the sensitive function value is 355.1478 which is very less as compared to others locations. After finding the optimum location in line no.7, the UPFC is placed and the OPF problem is solved using I-WDO algorithm. Table 2 depicts the results of OPF with UPFC incorporated in line no.7.

It is observed that with the incorporation of UPFC, the total fuel cost is reduced to 756.51 $/hr and the transmission losses are observed to be 4.55 MW. The cost and losses are reduced with proper operation of UPFC compared to base case.

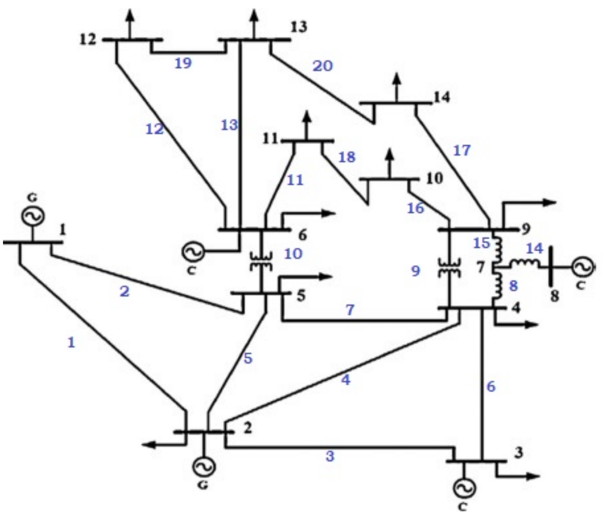

Fig 4. Single line diagram of IEEE 14 bus system.

The active power loss comparison and loss comparison is shown in Figs 5 and 6. From the obtained results, it can be observed that without the incorporation of UPFC the cost obtained is 767.97 $/hr while with the installation of UPFC it is reduced to 756.51 $/hr.

Table 2. Results of OPF with UPFC

S.No	Bus No.	Active Power Generation (MW)	Cost ($/hr)	Active Power Losses (MW)
1	1	95.06		
2	2	79.24		
3	3	38.90	756.51	4.55
4	6	22.24		
5	8	28.09		

In this analysis the cost of UPFC device is not considered. In the Fig 6, the variation of transmission losses are observed to be high in without case i.e 4.62 MW while it is reduced to 4.55 MW with the installation of UPFC. The OPF problem is solved with the help of I-WDO algorithm.

The comparison of fuel cost with and without UPFC are shown in Fig 7 and 8 with various algorithms. In Fig 7, the fuel cost is obtained with I-WDO, PSO, GA and DE without installing UPFC. It is observed that, the fuel cost with I-WDO is 767.97 $/hr. By using PSO it is 770.24 $/hr, with the help of GA the fuel cost is 820.42 $/hr and with the use of DE the fuel cost observed to be 790.15 $/hr. Hence, without installing UPFC, I-WDO leads to min fuel cost compared to other algorithms.

Fig 8 shows the fuel cost with I-WDO, PSO, GA and DE by installing UPFC. It is observed that, the fuel cost with I-WDO is 756.51 $/hr. By using PSO it is 762.87 $/hr, with the help of GA the fuel cost is 799.47 $/hr and with the use of DE the fuel cost observed to be 770.95 $/hr. Hence, with the installation of UPFC, I-WDO leads to minimum fuel cost compared to other algorithms.

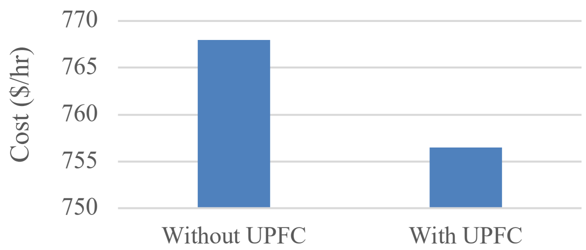

Fig 5. Fuel Cost with and without UPFC Using I-WDO.

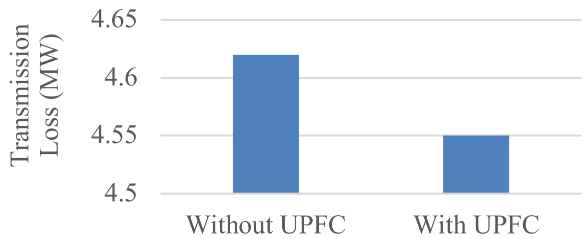

Fig 6. Transmission Loss with and without UPFC Using I-WDO.

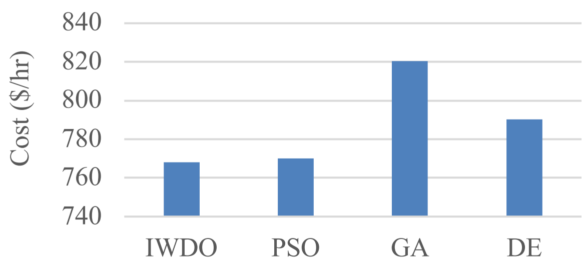

Fig 7. Fuel cost comparison without UPFC Using I-WDO, PSO, GA and DE algorithms.

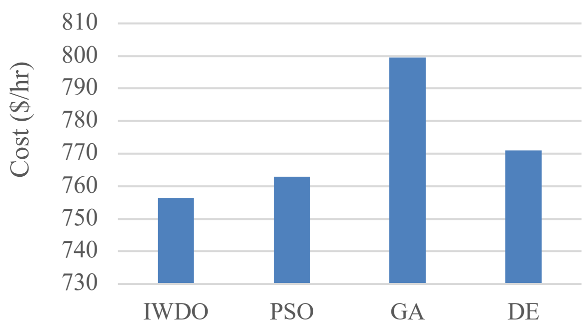

Fig 8. Fuel cost comparison with UPFC Using I-WDO, PSO, GA and DE algorithms.

The Figures 9 and 10 shows the variation of transmission loss with and without UPFC by applying different algorithms.

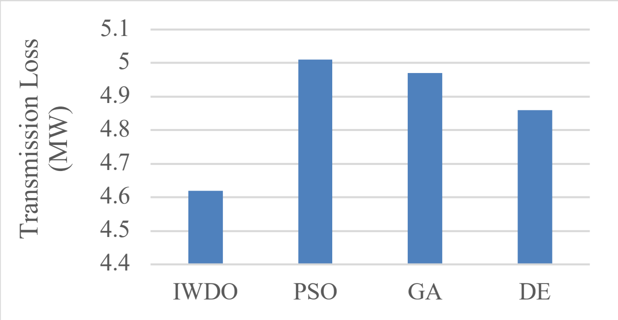

Fig 9. Transmission loss comparison without UPFC Using I-WDO, PSO, GA and DE algorithms.

In Fig 10, the transmission loss is obtained with I-WDO, PSO, GA and DE without installing UPFC. It is observed that, the loss with I-WDO is 4.62 MW. By using PSO it is 5.01 MW, with the help of GA the loss is 4.97 MW and with the use of DE the transmission loss observed to be 4.86 MW. Hence, without installing UPFC, I-WDO leads to min transmission loss compared to other algorithms.

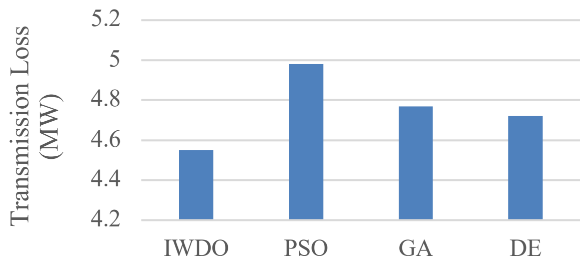

Fig 10. Transmission Loss Comparison.

7. Conclusion

In this paper, a novel I-WDO is proposed by inspiring from natural behavior of movement of air particles. With this proposed algorithm, the OPF problem is solved, cost and losses are obtained. To extract the benefit from FACTS devices the UPFC is placed in the system with properly identifying its location depending on sensitive function. With the incorporation of UPFC the cost and losses are also obtained. It is observed that with the incorporation of UPFC, the fuel cost and losses are reduced compared to the base case. The results obtained with proposed I-WDO algorithm are compared with that of PSO, GA and DE algorithms. From the obtained results it is observed that I-WDO outperformed over the remaining considered PSO, GA and DE algorithms.

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