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Comparative Analysis of a Performance of Metaheuristic Algorithms in Solving Optimal Power Flow Problems with UPFC Device in the Transmission System

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Abstract: ***Incremental industrialization and urbanization is the cause of enhanced energy use as it increases the building of new lines and more inductive loads. As a result, the transmission system losses increased, and the magnitudes of voltage profile values deviated from the stated value, resulting in increased cost of active power generation. To mitigate these issues, adequate reactive power compensation in the transmission line and bus systems should be done. Reactive power is regulated by the proper position of the Flexible AC Transmission System (FACTS). Unified Power Flow Controller (UPFC) is a voltage converter system that increases the voltage profile and reduces loss. In this paper, the optimal power flow solution is considered using a FACTS device based on Multi Population Modified Jaya (MPMJ) optimization algorithm. Using the Analytical Hierarchy Process (AHP) system, the optimal position of the UPFC device is determined by considering the most useful objective function provided by priorities and weighting factors. Therefore, on the standard IEEE-57 bus test system, the proposed MPMJ optimization algorithm is implemented with UPFC for optimal fuel cost values of generation, real power loss, voltage deviation and sum of squared voltage stability index. The result obtained by the proposed algorithm is contrasted with the recent literature algorithm.***

Keywords: ***Analytical Hierarchy Process, Meta-heuristic algorithm, MPMJ, Optimal Power Flow, UPFC***

I. INTRODUCTION

With regional grid interconnection, complete electricity market deregulation and increased power demand, power grids are becoming more complex. Power engineers find ways to best use their transmission systems. Optimal power flow with generation reallocation is a practical approach to better use of the existing system. Optimization is a way of extracting the best output under conditions. However, the optimized power system is not sufficient due to power generation reallocation, and more refinement is required in the system. In power systems, shunt capacitors are typically installed to support system voltages at acceptable levels.

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Series capacitors are used to reduce transmission lines' reactance, thus increasing the power transfer capacity of lines. Phase-shifting transformers are used to control power flows in transmission lines by adjusting the phase between transmitting and receiving end voltages.

In recent years, advances in power electronic devices have led to controllers' production, offering controllability and power transmission flexibility. Flexible AC Transmission System (FACTS) controllers were developed, and nowadays, their use in controlling power transmission is increasing [1]. The second-generation FACTS devices, such as the Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC), have a wide range of power system operation and control applications. UPFC is a flexible system that can monitor the power flow parameters, i.e. bus voltage, phase angle, and line reaction, individually or combined. In 1995, the UPFC FACTS system was first installed at Inez's Eastern Kentucky (USA) substation to increase power transmission capacity and provide voltage support [1], [2]. These FACTS devices have a great potential to make power systems more versatile, safe and cost-effective. The UPFC FACTS device combines series (SSSC device) and shunt (STATCOM device). It has high flexibility to control active power, reactive power, and voltage simultaneously [3]. Unified power flow controller (UPFC) integrated with OPF using the static model in this paper. UPFC FACTS system reduces overall generator fuel costs subject to power balance limitation, actual and reactive power generation limits, voltage limits, transmission line limits, and UPFC FACTS limits. The Analytical Hierarchy Process (AHP) approach proposed determining the optimal location of the UPFC FACTS device in the transmission line. The proposed Multi Population-based Modified Jaya algorithm compared its performance with the Teaching learning-based optimization and Jaya algorithm. The proposed algorithm derived from the Jaya algorithm, including multi population-based for controlling the population's diversity for fast convergence and get optimal values. The OPF solution with UPFC device is determined for the objective function of the generator's fuel cost, active power loss, the sum of voltage deviation, and enhancement of voltage stability index using the standard IEEE-57 bus test system.

II. MODELLING OF UPFC FACTS DEVICES

UPFC FACTS system is one of the most versatile FACTS systems capable of voltage management, series compensation, and phase shift, and can regulate line voltage and power flows. The steady-state UPFC mathematical model can be obtained by integrating bus m shunt power injection and bus n series power injection. Figure 1 shows UPFC's schematic equivalent power injection model. The UPFC device is both shunt and series controller so that according to the case study of this paper model analysis, it is getting better than both STATCOM and SSSC FACT devices. Neglecting converter losses and related coupling transformers during steady-state operation does not absorb or inject real power into the system [2]. The active power balance of the UPFC becomes;

$$P_p + P_s = 0 \tag{1}$$

However, both series and shunt converters can independently absorb or supply reactive electricity. The shunt converter's reactive power can be used to control bus m voltage in the AC system.

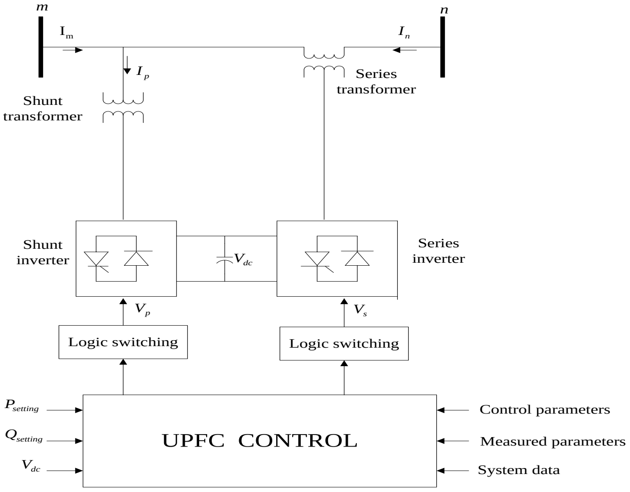

Figure 1. Functional block diagram of UPFC

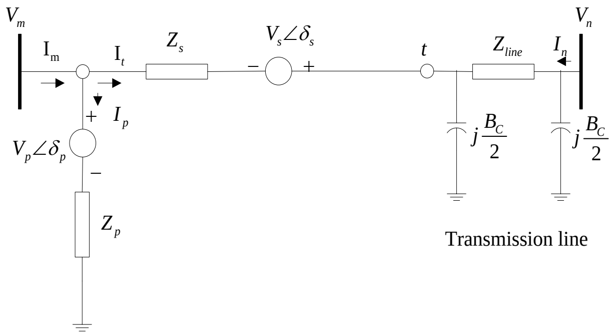

Figure 2. Equivalent circuit of UPFC FACTS devices

The power flow equation in the transmission line

$$\begin{aligned}
S_{mn} &= P_{mn} + jQ_{mn} = V_m\left(Y'_{mm}\left(V_m + V_s\right) + Y'_{mn}V_n + Y'_p\left(V_p - V_m\right)\right)^* \\
S_{nm} &= P_{nm} + jQ_{nm} = V_n I'_{nm} = V_n\left(Y'_{nm}\left(V_m + V_s\right) + Y'_{nn}V_n\right)^*
\end{aligned} \tag{2}$$

Active and reactive power flow with the UPFC FACTS device can be:

$$\begin{aligned}
P_{mn} &= G'_{mm}\left(V_m^2 + V_m V_s \cos\delta_{ms}\right) + G'_{mn}\left(V_m V_n \cos\delta_{mn}\right) + G'_p\left(V_m V_p \cos\delta_{mp}\right) \\
&- B'_{mm}\left(V_m V_s \sin\delta_{ms}\right) - B'_{mn}\left(V_m V_n \sin\delta_{mn}\right) - B'_p\left(V_m V_p \sin\delta_{mp}\right) \\
Q_{mn} &= G'_{mm}\left(V_m V_s \sin\delta_{ms}\right) + G'_{mn}\left(V_m V_n \sin\delta_{mn}\right) + G'_p\left(V_m V_p \sin\delta_{mp}\right) \\
&+ B'_{mm}\left(V'_{mm} + V_m V_s \cos\delta_{ms}\right) + B'_{mn}\left(V_m V_n \cos\delta_{mn}\right) + B'_p\left(V_m V_p \cos\delta_{mp}\right)
\end{aligned} \tag{3}$$

Similarly

$$\begin{aligned}
P_{nm} &= G'_{nm}\left(V_n V_m \cos\delta_{nm} + V_n V_s \cos\delta_{ns}\right) + G'_{mm}V_n^2 - B'_{nm}\left(V_n V_m \sin\delta_{nm} + V_n V_s \sin\delta_{ns}\right) \\
Q_{nm} &= -G'_{nm}\left(V_n V_m \sin\delta_{nm} + V_n V_s \sin\delta_{ns}\right) + B'_{nn}V_n^2 + B'_{nm}\left(V_n V_m \cos\delta_{nm} + V_n V_s \cos\delta_{ns}\right)
\end{aligned} \tag{4}$$

Finally, the power loss on the transmission line can be found by:

$$\begin{aligned}
P_{Ll} &= V_m^2 G'_{mm} + V_n^2 G'_{nn} + 2V_m V_n G'_{mn}\cos\delta_{mn} + V_m V_p\left(G'_p \cos\delta_{mp} - B'_p \sin\delta_{mp}\right) \\
&+ V_m V_s\left(G'_{mm}\cos\delta_{ms} - B'_{mm}\sin\delta_{ms}\right) + V_n V_s\left(G'_{nm}\cos\delta ns - B'_{nm}\sin\delta_{ns}\right)
\end{aligned} \tag{5}$$

The injected currents I_{minj} , and I_{ninj} can be obtained and their relationship with Vs and Vp is:

$$\begin{bmatrix} I_{min\,j} \\ I_{ninj} \end{bmatrix} = \begin{bmatrix} -\dfrac{Y_{mm}^2 Z_s}{1+Y_{mm}Z_s} + \dfrac{1}{Z_p} & -\dfrac{Y_{mm}Y_{mn}Z_s}{1+Y_{mm}Z_s} \\ -\dfrac{Y_{mm}Y_{mn}Z_s}{1+Y_{mm}Z_s} & -\dfrac{Y_{mn}Y_{nm}Z_s}{1+Y_{mm}Z_s} \end{bmatrix} \begin{bmatrix} V_m \\ V_n \end{bmatrix} + \begin{bmatrix} \dfrac{Y_{mm}}{1+Y_{mm}Z_s} & -\dfrac{1}{Z_p} \\ \dfrac{Ynm}{1+Y_{mm}Z_s} & 0 \end{bmatrix} \begin{bmatrix} V_s \\ V_p \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} I_{minj} \\ I_{ninj} \end{bmatrix} = \begin{bmatrix} Y'_{mm} & Y'_{mn} \\ Y'_{nm} & Y'_{nn} \end{bmatrix} \begin{bmatrix} V_m \\ V_n \end{bmatrix} + \begin{bmatrix} Y'_{mm} & Y'_p \\ Y'_{nm} & 0 \end{bmatrix} \begin{bmatrix} V_s \\ V_p \end{bmatrix} \tag{7}$$

Where

$$Y''_{mm} = G''_{mm} + jB''_{mm} = -\frac{Y_{mm}^2 Z_s}{1+Y_{mm}Z_s} + \frac{1}{Z_p}, Y''_{nn} = G''_{nn} + jB''_{nn} = -\frac{Y_{mn}Y_{nm}Z_s}{1+Y_{mm}Z_s}$$

$$Y''_{mn} = Y'_{nm} = G''_{mn} + jB''_{nm} = -\frac{Y_{mm}Y_{mn}Z_s}{1+Y_{mm}Z_s}$$

The injected power at bus m (Sminj), and bus n-(Sinj) formulated as:

$$\begin{aligned}
S_{min\,j} &= V_m I_{minj} \\
S_{ninj} &= V_n I_{ninj}
\end{aligned} \tag{8}$$

From equation (4.15), and (4.22) the injected real power at bus-m (Pminj) and reactive power (Qminj) of a transmission line having a UPFC are as follows.

$$\begin{aligned}
P_{\min j}^{UPFC} &= V_m^2 G_{mm}^{''} + V_m Vn\left(G_{mn}^{''}\cos\delta_{mn} + B_{mn}^{''}\sin\delta_{mn}\right) \\
&+ V_m V_s\left(G_{mm}^{'}\cos\delta_{ms} - B_{mm}^{''}\sin\delta_{ms}\right) + V_m V_p\left(G_p^{'}\cos\delta_{mp} - B_p^{''}\sin\delta_{mp}\right) \\
Q_{\min j}^{UPFC} &= V_m^2 B_{mm}^{''} + V_m Vn\left(G_{mn}^{''}\sin\delta_{mn} + B_{mn}^{''}\cos\delta_{mn}\right) \\
&+ V_m V_s\left(G_{mm}^{'}\sin\delta_{ms} + B_{mm}^{'}\cos\delta_{ms}\right) + V_m V_p\left(G_p^{'}\cos\delta_{mp} + B_p^{'}\cos\delta_{mp}\right)
\end{aligned} \tag{9}$$

Similarly, the real power $P_{n\text{in } j}^{UPFC}$, and reactive power $Q_{n\text{in } j}^{UPFC}$ injection at the bus –n is:

$$\begin{aligned}
P_{n\text{in } j}^{UPFC} &= V_n^2 G_{nn}^{''} + V_m Vn\left(G_{nm}^{''}\cos\delta_{nm} + B_{nm}^{''}\sin\delta_{nm}\right) + V_n V_s\left(G_{nm}^{'}\cos\delta_{ns} - B_{nm}^{''}\sin\delta_{ns}\right) \\
Q_{n\text{in } j}^{UPFC} &= V_n^2 B_{nn}^{''} + V_m Vn\left(G_{nm}^{''}\sin\delta_{nm} + B_{nm}^{''}\cos\delta_{nm}\right) + V_n V_s\left(G_{nm}^{'}\sin\delta_{ns} - B_{nm}^{'}\cos\delta_{ns}\right)
\end{aligned} \tag{10}$$

The mathematical formulation of UPFC device which mentioned in equation (10) is incorporated with Newton Raphson load flow equation for further optimal power flow solutions.

III. MATHEMATICAL FORMULATIONS OF OPTIMAL POWER FLOW

The optimum power flow problem is primarily about minimizing the fuel cost of active power generations and power losses in the power system, given the system's operating limits.

The optimal power problem aims to find an optimal profile of active and reactive power generations along with voltage magnitudes in such a way as to reduce the overall operating costs of a thermal power system while meeting network protection constraints. The constraint minimization problem can be transformed into an unconstrained one by increasing load flow constraints into the objective function. Some well-known four forms of objective OPF problem are defined as:

Objective Function I: Min $f_1 = \sum_{i=1}^{NG} (a_i P^2{}_{gi} + b_i P_{gi} + c_i)\$/h$ is the total generation cost function

Objective Function II:

Min $f_2 = P_L = \sum_{i=1}^{N_l} g_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right]$

is the total real power loss

Objective Function III: Min $f_3 = \sum_{i=1}^{NL} \left(\left|V_i - 1\right|\right)^2$ is a total voltage deviation

Objective Function IV:

Min $f_4 = L_j = \left|1 - \sum_{i=1}^{ng} F_{ji}\frac{V_i}{V_j}\angle\theta_{ij} + \delta_i - \delta_j\right|$ is the sum of the squared voltage stability index.

Equality Constraints

The equality constraints for the proposed objective functions are as follows.

a) Real power constraints

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\cos\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \tag{11}$$

b) Reactive power constraints

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\sin\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \tag{12}$$

Inequality Constraints

The inequality constraints for the objective functions are as follows.

a) Generator constraints

$$\begin{aligned}
&P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, \ i=1\ldots NG \\
&V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max}, i=1\ldots NG \\
&Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i=1\ldots NG
\end{aligned} \tag{13}$$

b) Transformer constraints

$$T_i^{\min} \le T_i \le T_i^{\max}, \ i=1\ldots NT \tag{14}$$

c) Shunt Var compensator constraints

$$Q_{Ci}^{\min} \le Q_{GCi} \le Q_{Ci}^{\max}, i=1\ldots NG \tag{15}$$

d) Security constraints

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max}, i=1\ldots NL \tag{16}$$

$$S_{li} \le S_{li}^{\max}, i=1\ldots nl \tag{17}$$

e) UPFC FACTS device constraints

UPFC voltage magnitude and angles constraint

$$V_p^{\min} \le V_P \le V_p^{\max}$$
$$\delta_p^{\min} \le \delta_p \le \delta_p^{\max} \qquad (18)$$
$$V_s^{\min} \le V_s \le V_s^{\max}$$
$$\delta_s^{\min} \le \delta_s \le \delta_s^{\max}$$

IV. PROPOSED MULTI-POPULATION BASED MODIFIED JAYA (MMPJ) ALGORITHM

The JAYA algorithm is the most powerful meta-heuristic optimization algorithm for solving non-linear equations. Form the literature; the JAYA algorithm is applicable for optimal power flow solution to solve the Objective of fuel cost of generation, active power loss, sum of voltage deviation, and voltage stability index parameters.

Therefore, in this paper, the Multi Population-based Modified Jaya (MPMJ) algorithm was applied for the known objective function with UPFC device. The modified JAYA algorithm with multi-population has overcome the drawback of the original JAYA algorithm. Hence, the modified JAYA algorithm is derived by changing the original JAYA algorithm's mathematical equation to update into the solution of equation (19). Multi-Population based methods can solve real-world optimization problems in all disciplines. In this paper, we applied the subpopulation number based Multi Population methods for the modified JAYA algorithm. The multi-population Modified JAYA algorithm is shown in Figure 3.

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}[(X_{j,best,i}) - (|X_{j,k,i}|)] - r_{2,j,i}[(X_{j,worst,i}) - (|X_{j,k,i}|)] \qquad (19)$$

In the proposed modified JAYA algorithm, an elite member in the population acts as a reference to other population members to boost their positions near the best-known position. For the proposed modified Jaya algorithm, the mathematical equation can be shown in equation (20).

$$X'_{j,k,l} = X_{j,k,i} + r_{1,j,i}[(X_{j,worst,i}) - (|X_{j,k,i}|)] - L * r_{2,j,i}[(|X_{j,k,i}|^2) - (X_{j,best,i})] \qquad (20)$$

Where L is a coefficient determined in each iteration as follows:

if rand > 0.5 then L =1;

else L=-1;

end. Since the rand value the number between 0 and one.

The multi population-based algorithm is mostly applicable to control population diversity.

The characteristics of a multi population-based Algorithm are useful in the following ways [5].

- The overall diversity of the population is maintained by grouped population based on the similarities at all
- Having the ability to search in various regions
- The population-based optimization algorithm is easily compatible with the multi-population method

In general, selecting the number of a subpopulation is a very critical issue in this multi-population-based algorithm.

From Figure 3, the algorithm steps for the multi-population algorithm can be explained in the following steps

Step 1: Fix the number of population or initial population (p), design variables, and maximum termination values

Step 2**:** Calculate the initial solution for the objective function (fuel cost of generation, active power loss in the transmission line, sum of voltage deviation, and voltage stability index) by considering the equality and inequality constraints.

Step 3**:** Divide the population into subpopulation based on the quality of the solution according to the test solution of the objective function (i.e., initially, the value of m=2 is considered)

Step 4: The multi population-based modified Jaya algorithm equation to modify the solution in each group autonomously for each subpopulation. The modified solution is accepted if the new solution is better than the old solution.

Step 5: Combine the entire sub solution, check whether the Objective (best before) is better than the Objective (best after). Objective (best before) is the best solution for the entire population and Objective (best after) is the current best solution in the entire population. If the value of Objective (best after) is better than the value of Objective (best before), m is increased by 1 (i.e., m=m+1) algorithm needs more exploration feature. Otherwise, m is decreased by 1 (i.e., m= m-1) as the algorithm needs to be more exploitive than explorative.

Step 6: Check the stopping condition(s). If the search process has reached the maximum number of iterations, then terminate the loop and report the solution. Otherwise, go to step 3, and re-divide the population, and repeat some process.

Generally, the pseudo-code of the multi-population based algorithm discussed in the following [8].

Initialized the total population (n), design variable, and maximum number iteration (Nmax), where the maximum number of functions evacuations.

Generate the initial objective function solution and set current generation j=1

While j<Max

j=j+1; then divide the population into m subpopulation based on the objective function's quality and several design variables. $P_1, P_2, P_3 \ldots P_m$

For k=1:m, Identify the best and worst solution among P_k

For L=1: round (P/m), $P'_{k,L}$ modify the solution's parameters using a modified JAYA algorithm equation (2).

End for

If $O(P'_{k,L})$ better than $O(P_{k,L})$ $\quad P_{k,L} = P'_{k,L}$,

Else, $P_{k,L} = P_{k,L}$

End if

End for, merge the entire sub-population ($P_1, P_2, P_3 \ldots P_m$) into P

Else if $m > 1$,m=m-1

End if

End while

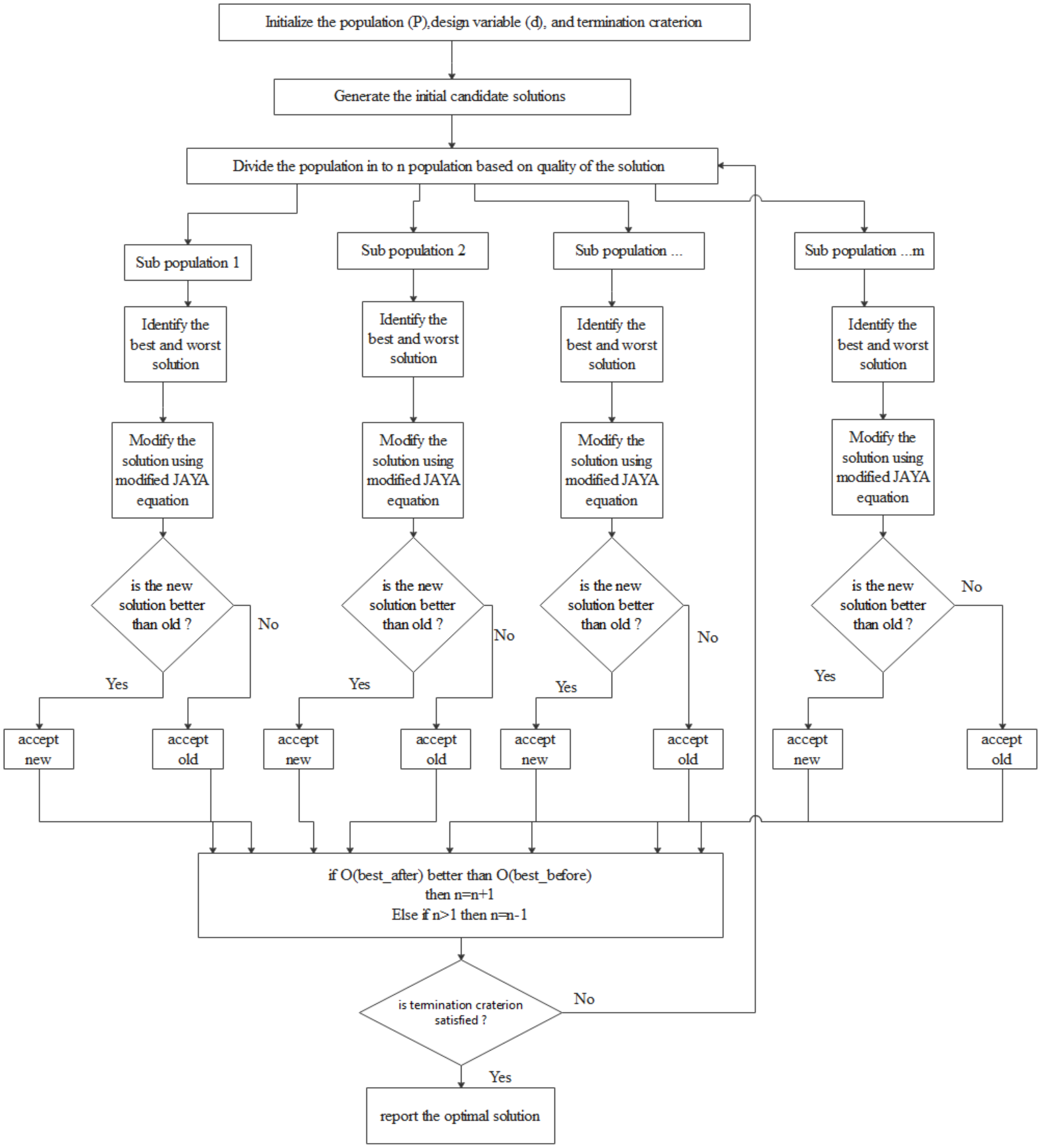

Figure 3. The basic flow chart of the MPMJ algorithm

Implementation steps of the proposed MPMJ algorithm to OPF without and with UPFC device:

Step 1: Initialize the number of population and design variable

The Multi Population-based Modified Jaya algorithm is parameterless. There is no tunning parameter, only initialize the number of population (N), design variable (D), and a maximum number of iteration (Itermax) for MPMJ are chosen and are declared.

Step 2: Declaration of data

The data such as bus data, line data, tap setting of regulating transformer, load data, generator information data, and UPFC device locations are declared.

Step 3: Initialization

Generation count set to, iter=0, Initialize a set of random values for real power generation, generator voltages, transformer tap settings, and reactive power injections of population NP within acceptable range using the equation below:

$$P_{G,0} = rand(0,1).(P_{Gi}^{\max} - P_{Gi}^{\min}) + P_{Gi}^{\min},$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1,\ldots,ng$$

$$V_{G,0} = rand(0,1).(V_i^{\max} - V_i^{\min}) + V_i^{\min},$$

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,\ldots,ng$$

$$T_{G,0} = rand(0,1).(T_i^{\max} - T_i^{\min}) + T_i^{\min},$$

$$T_i^{\min} \le T_i \le T_i^{\max}, i = 1,\ldots,nt$$

$$Q_{G,0} = rand(0,1).(Q_i^{\max} - Q_i^{\min}) + Q_i^{\min},$$

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i = 1,\ldots,cs$$

$$X_0 = [P_{G,0}, V_{G,0}, T_{G,0}, Q_{G,0}].$$

Step 4: Run the Newton-Rapson load flow without and with UPFC device with this initial population to check the feasibility of the solution and satisfaction of equality an inequality constraint.

Step 5: Allocate the UPFC device on the weakest bus. The weakest bus is determined using the voltage stability index. The value of the voltage stability index approach to one or beyond one becomes a weak bus. Similarly, as the bus stability index is near to zero, the system becomes stable, and no need for compensation.

Step 6: Define the objective function to be optimized individually, given below.

$$f_1 = F(P_G) = \sum_{i=1}^{ng}\left(a_i P_{Gi}^2 + b_i P_{Gi} + c_i\right),$$

$$f_2 = P_L = \sum_{i=1}^{N_l} g_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right]$$

$$f_3 = L_j = \left|1 - \sum_{i=1}^{ng} F_{ji}\frac{\bar{V}_i}{\bar{V}_j}\right|,$$

$$f_4 = \text{VD} = \sum_{i=1}^{nb}\left(\left|V_i - 1\right|\right)^2$$

Step 7: Run the power flow application for each candidate solution with the UPFC device for all objective functions.

Step 8: Identify the best and worst solutions among the candidate solutions.

Step 9: Based on the value of best and worst conditions, modify all the candidate solutions, the proposed multi population-based modified Jaya algorithm modifications expressed using the modified equation. Based on the flow chart in Figure 3, and pseudo-code of multi-population, divide the population into subpopulation, compare the new solution with the old solution for each subpopulation, and finally identify the best discarded the worst solution.

Step 10: For all updated solutions, if any control variable is beyond the limits, replace the values within the maximum or minimum limits.

Step 11: Run the Newton-Raphson load flow method without and with the UPFC device with these modified control variables to check the feasibility of the solution and satisfaction of equality and inequality constraints. Calculate the objective function values and add the penalty functions to the objective function if the limit's volitation uses penalty function equation.

Step 12: For each solution, compare the objective function from the previous values and the updated solution. Accept the updated solution is that the values are better than the previous values. Otherwise, keep the previous solution

Step 13: The program terminates if the termination criterion is achieved, else the program continues from step 8.

V. RESULT AND DISCUSSION

The effectiveness of the metaheuristic TLBO, JAYA, and proposed MPMJ Algorithm without, and with UPFC device are examined on the standard IEEE-57 bus system to test the system for OPF problems. The optimal allocation of the UPFC device on the transmission line is selected using the Analytical Hierarchy Process (AHP) method. The proposed algorithm's simulation results under different objective functions are compared with other Metaheuristic algorithms and intelligent methods from the recent literature. The voltage magnitudes (V) and phase angles (δ) of the power system are initialized randomly within the specified limits. The limits of voltage magnitudes at the shunt and series converter, real and reactive power reference is obtained from reference [4]. All the optimization programs are coded in MATLAB 2015a programming language and run on a 1.19 GHz personal computer with 8 GB RAM.

The proposed method is tested under normal operating conditions. Under this operating condition, the optimal power flow simulations are carried out without and with the UPFC device at five selected buses. Finally, the overall best location of the UPFC device is obtained using the Analytical Hierarchy Process (AHP) methods. In each case study, each objective function is optimized individually. Also, the obtained results are compared with those reported in the literature. The case studies for simulation are as follows under normal operating conditions:

Case I: Single-objective optimization without UPFC device

Case II: Single-objective optimization with UPFC device at the selected locations

Case III: Application of AHP methods for determination of the optimal location of UPFC device

a. Case I: Single-objective optimization without UPFC device

In this section, the proposed comparison techniques of optimal power flow solutions are evaluated using the IEEE-57 bus system. There is a lot of optimization algorithm in the literature review to solve the optimal power flow solution. In this paper, compare to the metaheuristics TLBO, JAYA, and proposed MPMJ algorithm in terms of getting optimal values of the objective functions (minimizing of fuel cost of the generator, minimizing of active power loss, the sum of voltage deviation improvement, and enhancement of voltage stability index on the bus), and convergence characteristics for the IEEE-57 bus system.

In each case study, 10 test runs were performed for solving the OPF problems.

Figures 5 (a)-(d) shows the variations of total fuel cost of the generator, active power losses, sum of bus voltage deviation, and voltage stability index for the original power system without connecting any UPFC device IEEE-57 bus system. It is seen from Figures 5 (a)- 5(d), it can be observed that the proposed MPMJ algorithm reaches the best solution within a few numbers of iterations under all objective functions. This shows the convergence reliability of the proposed MPMJ algorithm.

Figure 5(a) shows the convergence of fuel cost of generation of the IEEE 57-bus test system under normal operating conditions. The minimum costs obtained using TLB, JAYA, and proposed MPMJ algorithms are 41622$/hr, 41619$/hr, and 41614$/hr, respectively. Figure 5(b) shows the convergence of total real power loss of the IEEE 57-bus system under normal operating conditions. The minimum power losses obtained using TLBO, JAYA, and proposed MPMJ algorithms are 0.1521p.u, 0.1481pu and 0.1480pu respectively. Figure 5(c) shows the convergence of the sum of voltage deviation of the IEEE 57-bus system under normal operating conditions. The minimum sum of voltage deviation obtained using TLBO, JAYA, and proposed MPMJ algorithms are 1.0111p.u, 0.8561pu and 0.701pu respectively. Figure 5(d) shows the convergence of voltage stability index the IEEE 57-bus system under normal operating conditions. The minimum of voltage stability index obtained using TLBO, JAYA, and proposed MPMJ algorithms are 0.2651p.u, 0.2578p.u and 0.2467p.u, respectively. From Figures 5(a)-5(d), it can be observed that the proposed MPMJ algorithm reaches the best solution within a few numbers of iterations under all objective functions of the IEEE 57-bus system without UPFC device.

Table. 5 summarized all objective function results in comparisons with recent literature. From Table 5, it is clear that the proposed method can achieve better results concerning other algorithms. These values are not negligible because of the continuous operations of power dispatch throughout the years.

b. Case II: Single-objective optimization with UPFC device at the selected locations

The proposed MPMJ algorithm is applied for solving the optimal power flow problems subjected to different equality and inequality constraints with the location of the UPFC device in the selected buses under normal operating conditions. The selected locations of UPFC are the lines 9-13,9-12,56-41,9-10 and 54-55. These locations are taken based on the first five maximum voltage stability index of the lines from the transmission line's steady-state values. The value of the voltage stability index at lines 9-13,9-12,56-41,9-10, and 54-55 is 0.1747, 0.1667, 0.1652,0.1649, and 0.1402 respectively. The line stability index for all the transmission line is shown in Figure 4.

The proposed MPMJ algorithm is applied for solving the OPF problem with four different objective functions. In each case study, four sets of 10 test runs were performed for solving the OPF problems under normal operating conditions. All the solution satisfies the constraints on reactive power generation limits and line flow limits.

Table 1 gives the total fuel cost of generation, total real power loss, voltage stability index, and the sum of voltage deviation with the UPFC device at the selected locations for IEEE-57 bus. Table 1 shows that each candidate bus has given minimum attributes (objective function value) as the best value compared to optimization without the UPFC device. Also, from Table 1, it can be observed that under normal conditions, the optimal value for the cost of generation is 41606$/hr at line 54-55, the optimal value for power loss is 0.1019pu at line 9-13, the optimal value for voltage stability index is 0.221 at line 56-41, an optimal value for the sum of voltage deviation is 0.6pu at line 56-41. With this, one can say that under normal conditions, optimal values of four attributes are obtained at different alternatives. Therefore, it is tough to differentiate the best option from considered five alternatives that operate the power transmission system more effectively and efficiently. Hence, for achieving a result that meets some objectives, it is necessary to use the Analytical Hierarchy Process method. Thus, after solving the OPF problem for different alternatives of the objective functions/attributes, these values are given as input to AHP methods to select the best location for UPFC installation in the IEEE 57-bus test system.

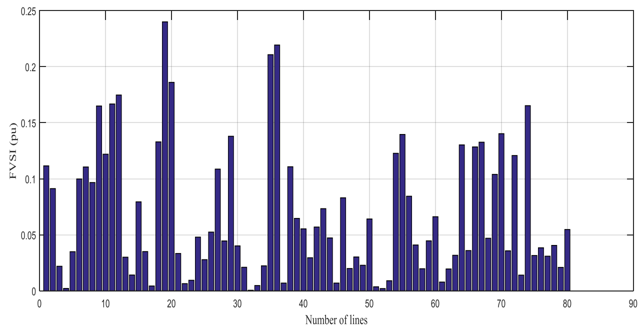

Figure 4. Line stability index for the IEEE-57 bus system

c. Case III: Application of AHP methods for determination of the optimal location of UPFC device

To get the optimal operation of the power system within the constraint, the selection of the best location of FACTS devices plays an essential role in the process of the power system. Therefore, different techniques are explained in the literature to select the best position of FACTS devices.

Still, the methods are their advantages, and the disadvantages depend on the system's optimal operation. In this paper, the Analytical Hierarchy Process (AHP) is used to select the UPFC FACTS device's best position since the AHP methods considered all the four objectives of fuel cost of the generator, active power loss, sum of bus voltage deviation, and voltage stability index.Thus, the AHP method is applied to differentiate the best alternative out of five considered alternatives. The optimal power flow solution is displayed in Table 1 for five weakest lines using the proposed MPMJ algorithm, since as compared in Table 6 with TLBO, and JAYA, the proposed MPMJ algorithm-based result is the most optimal.

The OPF results with the UPFC device are shown in Table 1 used as a decision matrix for the system and then given as an input to the AHP method. From Table 1, one or two alternatives provide the best value when compared to optimization with UPFC located at other alternatives. The pairwise comparison matrix given in Table 2 determines the preference of each attribute over another. In pairwise comparison Table 2, diagonal elements are taken as 1, which means objectives are of equal importance. The upper diagonal elements of the matrix have been taken by giving preferences to the attributes, and the lower diagonal elements of the matrix have been taken as a reciprocal of the upper diagonal elements of the matrix. In upper diagonal elements of the matrix, the first-row second column is taken as 2, which means that the cost attribute is the intermediate values of the power loss attribute. The first row third and fourth columns are taken as 3 that means that cost attribute is slightly more important than values of the sum of squared voltage stability index and total voltage deviation attributes. Similarly, the second-row third column is taken as 2, which means the power loss attributes the sum of squared voltage stability index intermediate values. The second-row fourth column is taken as 5, which means the power loss attribute is more important than values of the total voltage deviation attribute. Finally, the third-row fourth column is taken as 2 mean the voltage stability index value is the intermediate of voltage deviation.

From the Table 3, it is observed that 39.05% percentage of priority is given to the cost attribute, 27.61% per cent priority is given to the power loss attribute, 19.53% per cent priority is given to the voltage stability index, and 13.81% is given to the sum of voltage deviation attributes. Table 3 shows that the total fuel cost of generation is the essential criterion or attribute. The second most important criterion is the total real power loss. The third most important criterion is the voltage stability index and the least importance given to the voltage deviation attribute. This weight matrix or eigenvector determines the relative ranking of alternatives under each criterion.

Table 3 shows that the sum of all priority vector attributes is one and the Priority vector displays relative weights of the items we compare. Since the ration of consistency is less than 10%, it is appropriate, and the method is observable for optimal values of the proposed objective function.

Table 4 shows the relative ranking of alternatives under five objective functions: the minimization of fuel cost of the generator, minimizing the sum of voltage deviation, minimizing active power loss, and enhancing the voltage stability index by the AHP method. Therefore, from this, one can say that the AHP method under normal operating condition gives rank one to the alternative line 54-55 for the UPFC location to the IEEE-57 bus system. So, it is considered as an optimal location for UPFC device among the lines considered for the system, and this gives the highest benefits to the power system operation in terms of performance parameters.

From Table 6, under normal load case, it is clear that the control setting corresponding to the OPF with cost minimization with the UPFC device at line 54-55. The optimized fuel cost value using TLBO, JAYA, and proposed MPMJ algorithm is 41615$/h, 41613$/h, and 41606$/h, respectively. The total active power loss enhancement from 0.1234pu by TLBO to 0.1198pu by JAYA, and 0.1110pu by MPMJ algorithm. The sum of voltage deviation improved 0.8946pu by TLBO to 0.7402pu by JAYA, and 0.6110pu by MPMJ algorithm. Similarly, the minimum voltage stability index is enhanced from 0.248pu by TLBO to 0.239pu by JAYA, and 0.228pu by MPMJ Algorithm. In Table 6 the convergence time for the OPF results without and with the UPFC device under normal operating conditions are also compared. The convergence characteristic of each objective function with UPFC at line 54-55 is shown in Figures 6(a)-6(d), which shows smooth convergence to the optimum value without any abrupt oscillations for the best run under normal operating conditions respectively. Meanwhile, the optimal control variables settings for OPF without and with the UPFC device at line 54-55 under the normal operating condition for TLBO, JAYA, and proposed MPMJ algorithm

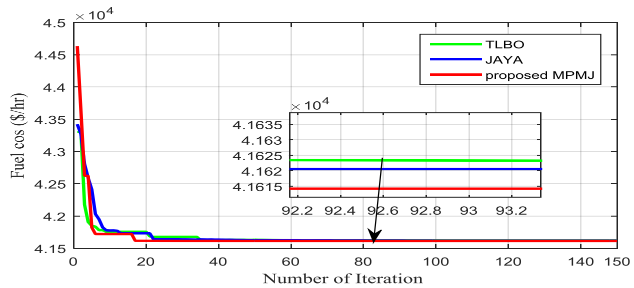

Figure 5(a). Convergence characteristic of total fuel cost without UPFC device

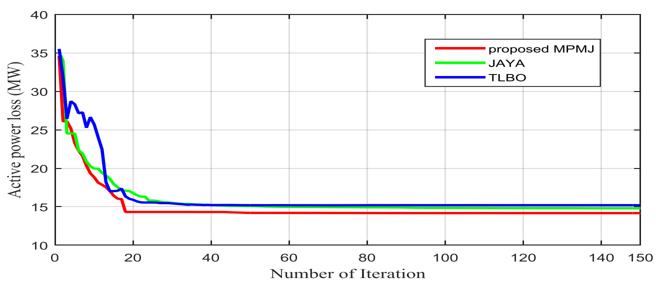

Figure 5(b). Convergence characteristic of total active power loss without UPFC device

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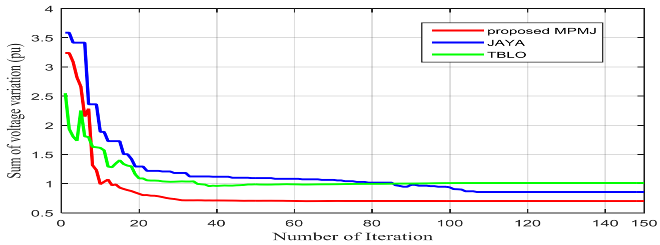

Figure 5(c). Convergence characteristic of total voltage deviation without UPFC device

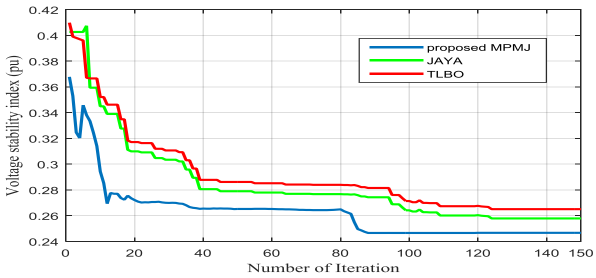

Figure 5 (d). Convergence characteristics of sum of squared voltage stability index without UPFC device

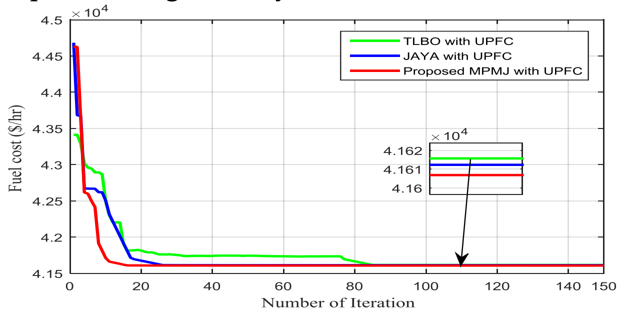

Figure 6 (a). Convergence characteristics of total fuel cost of the generation at the optimal location of UPFC at line 54-55

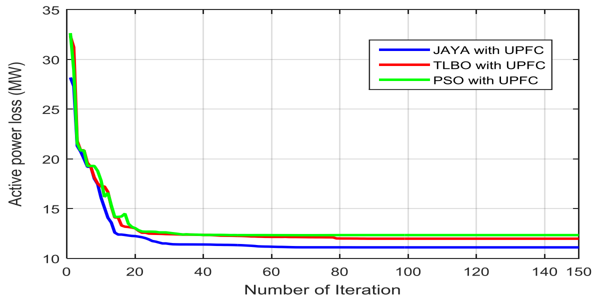

Figure 6 (b). Convergence characteristics of real power loss at the optimal location of UPFC at line 54-55

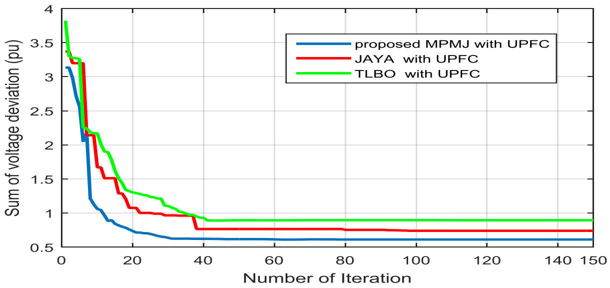

Figure 6 (c). Convergence characteristics of voltage deviation at the optimal location of UPFC at line 54-55

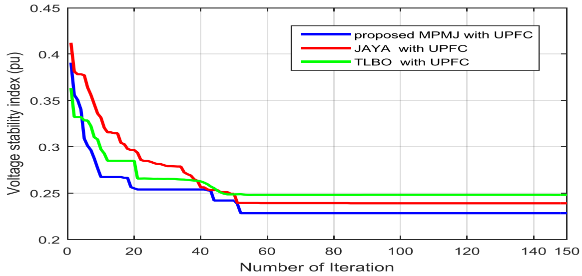

Figure 6 (d). Convergence characteristics of sum of squared voltage stability index at the optimal location of UPFC at line 54-55

Table 1. OPF results and decision table for the AHP method for IEEE-57 bus

Alternatives		Attributes			
From bus	To bus	Fuel cost ($/h)	Power loss (pu)	VSI (pu)	VD (pu)
9	13	41606.4	0.1019	0.233	0.648
9	12	41608.2	0.136	0.235	0.609
56	41	41607.0	0.1210	0.221	0.60
9	10	41606.8	0.1333	0.241	0.602
54	55	41606.0	0.11	0.228	0.611

Table 2. Pairwise comparison matrix for attributes for IEEE-57 bus

Objective	Attributes			
	Fuel cost	Power loss	VSI	VD
Fuel cost	1	2	3	3
Power loss	0.5	1	2	5
VSI	0.33	0.5	1	2
VD	0.33	0.2	0.5	1

Table 3. Weight matrix and value of attributes for IEEE-57 bus

Attributes	Weightage	Subjective measurement of attributes	Assigned values
Fuel cost	0.3905		
Power loss	0.2761	Eigen value	4.1213
VIS	0.1953	Consistency index	0.0404
VD	0.1381	Consistency ratio	0.0454

Table 4. Weakest bus ranking by AHP methods for IEEE-57 bus

From bus	To bus	AHP ranking
9	13	4
9	12	5
56	41	2
9	10	3
54	55	1

Table 5. Comparison of proposed MPMJ algorithm without and with UPFC device with recent methods

Algorithm	Fuel cost ($/h)	Real power loss (MW)	Voltage Deviation (p u)	L-Index
AMO [5]	41679.83	15.955	0.7582	NR
SSA [6]	41672	11.321	0.7569	0.259
MSA [7]	41673.72	15.0526	NR	0.27481
MVO [8]	41678.084	15.1751	NR	NR
CRO [9]	NR	25.3584	1.1796	0.5784
ICEFO [10]	41706.1117	15.72	0.6798	0.2740
CKHA [11]	41660.4657	15.45	0.7247	NR
MOALO [12]	41623.1352	14.81	0.830	NR
FCGCS [13]	41666.6316	NR	0.7507	0.2742
Proposed MPMJ	**41614**	**14.8**	**0.7011**	**0.2463**

Table 6. Performance parameters comparison for IEEE 57-bus test system without and with UPFC device at line 54-55

Algorithms	Performance parameters	Cost		Power loss		Voltage Deviation		Voltage stability index	
		without	with	without	with	without	with	without	with
TLBO	Fuel cost ($/hr.)	41622	41615	43000	42364.3	42248	42156	42080	42058
	Real power loss(pu)	0.172	0.166	0.1520	0.1234	0.19	0.186	0.20	0.194
	∑Voltage deviation(pu)	1.22	1.11	2.0595	1.984	1.0111	0.8946	2.04	1.984
	L-index	0.4871	0.411	0.312	0.30	0.368	0.3365	0.2651	0.248
	CPU time (s)	628.3	634.5	696.5	704	620.6	630	621.5	627.5
JAYA	Fuel cost ($/hr.)	41619	41613	42908	42354.88	42228	42137	42040	42008
	Real power loss(pu)	0.162	0.156	0.1481	0.1198	0.189	0.1840	0.198	0.192
	∑Voltage deviation(pu)	1.13	1.101	2.043	1.938	0.856165	0.7402	2.012	1.865
	L-index	0.4671	0.406	0.302	0.289	0.3632	0.3348	0.2578	0.239
	CPU time (s)	617.3	623.5	685.5	693	609.6	618.4	610.5	616
Proposed MPMJ	Fuel cost ($/hr.)	41614	41606	42906	42342.45	42216	42127.8	42030.4	42000.2
	Real power loss(pu)	0.1601	0.154	0.148	0.1110	0.178	0.1742	0.188	0.1818
	∑Voltage deviation(pu)	1.111	1.0994	2.022	1.910	0.701096	0.6110	1.986	1.844
	L-index	0.4571	0.401	0.3011	0.287	0.3582	0.3339	0.2467	0.228
	CPU time (s)	607.3	614	663.5	675.5	602.5	610	608.4	613

VI. CONCLUSION

This paper solves optimal power flow with the UPFC FACTS device's inclusion using the proposed MPMJ algorithm. The proposed algorithm compares and presents Teaching Learning-based optimization and JAYA algorithms without and with UPFC FACTS device considering different objective functions under normal operation performance for system performance enhancement. Also, the performance of the proposed algorithm compared with another algorithm in recent literature. The unified power flow controller (UPFC) is a versatile device capable of controlling the power system parameters corresponding voltage magnitude, phase angle and line impedance individually or in a combination.

The Analytical Hierarchy Process methods differentiate the best location for UPFC devices out of considered locations in terms of the systems' performance parameters. The suggested solution was successfully and efficiently applied to find optimal control variables settings. The simulation results on the IEEE 57 bus test systems have been presented for illustration purposes. In general, through the present case of optimal power flow solution with and without UPFC device, it has been observed that the proposed MPMJ algorithm provides reliable results with less computational efforts, time, and optimal results.

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