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Performance Study of A System with Optimal Location of STATCOM Device using MPMJ Algorithm under Normal Operating Conditions

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***Abstract*:- Optimal power flow solution is the backbone of power system operation, power system future design, stability analysis, and power system future expansion. To solve this optimal power flow problem, there are many traditional and meta-heuristics algorithms in the literature. The regular optimal power flow has visible limitations: it takes much time to converge and fails to produce the optimal values within the operating limits. Due to these drawbacks, the researcher shifted to a meta-heuristic algorithm. In this paper mainly devoted to minimize the fuel cost of the generator, improve the voltage magnitude, reduce active power loss, and voltage stability index using the mention meta-heuristic algorithm. The feasibility and effectiveness of the proposed algorithm approach are investigated and exemplarily demonstrated on the IEEE-30 bus test system. The performance of the optimal power flow performed by allocating the proper place of the STATCOM device using the Analytical Hierarchy Process (AHP). From the simulation result for the given objective, the metaheuristic TLBO, JAYA, and MPMJ algorithm compared with and without STATCOM. Besides, the comparison is made with similar studies in the literature. Based on the simulation result, the proposed MPMJ algorithm is the most powerful for the optimization algorithm for the defined objective and selected test system.**

Keywords: AHP, MPMJ, OPF, STATCOM, FACTS, Metaheuristic algorithm.

I. INTRODUCTION

Optimal power flow (OPF) is part of an integrated power system delivery solution. OPF main goal is to optimize the selected objective feature, including fuel cost, voltage stability indices, active and reactive power loss, and optimum power system control variables change. Nevertheless, it must satisfy reactive power limits on equality and inequality constraints [1]. The OPF problem was and remains one of the most investigated problems in power systems. Earlier, as stated in [2], several classical (deterministic) optimization algorithms were successfully applied, such as Interior point methods[3], [4], Newton's method [5], linear programming methods [6], non-linear programming and gradient method [7] are useful to solve optimal power flow besides, the conventional methods have strong limitations in convergence, and they cause complications in obtaining the overall optimal solutions.

Due to the problems mentioned above, the research focus has already shifted to the meta-heuristic algorithm. The varieties of Meta-heuristic Algorithm that can solve optimal power flow complication, like particle swarm optimizations (PSO) [8], a novel hybrid bat algorithm [9], Artificial Bee Colony algorithm (ABC) [10], and Fruit Fly optimization [11].

Analytical Hierarchy Process effectively supports decision making concerning complex sustainability issues and can help to recognize and define a problem in detail. It is widely used to decompose a decision problem into its essential parts, which are then structured hierarchically. As a result, AHP delivers a ranking of options which facilitate the selection of a strategy option [12].In this paper, the allocation of STATCOM FACTS device is applied on the bus by using Analytical Hierarchy Process (AHP) which in turn compares four parameters namely fuel cost of the generator, active power loss, sum of voltage magnitude on the bus and voltage stability index. We have to select five weakest buses using the voltage stability index. Then, based on these four parameters, we can determine the optimal bus using that AHP method.

II. MATHEMATICAL MODELLING OF STATCOM DEVICE

Active and reactive power flow determined by the phase angle difference between the sources and by the voltage magnitude difference, respectively. Hence, STATCOM can control reactive power flow by changing the fundamental component of the converter voltage concerning the AC bus voltage, both phase and magnitude sensible [12]. In [13], the placement of STATCOM FACTS device based on the PQ bus having low voltage magnitude and the rate STATCOM MVAr rating is between -100 & +100MVAr.

A mathematical model for the controller to the inclusion of load flow algorithm derived from the equivalent circuit diagram of STATCOM in Figure 2.

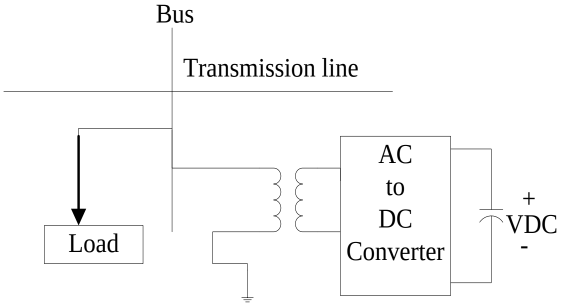

Figure 1. STATCOM schematic diagram

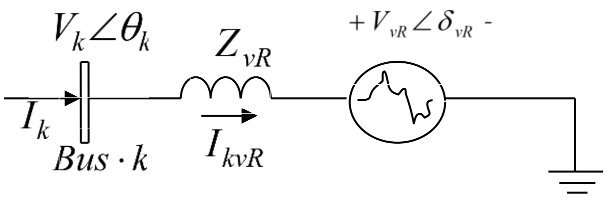

Figure 2. Equivalent diagram of STATCOM device

The STATCOM power flow equations are derived from first principles and assume the following voltage source representation.

$$E_{vR}=V_{vR}(\cos\delta_{vR}+j\sin\delta_{vR}) \quad 1$$

$$V_{vR}=V_k+Z_{vR}I_{vR} \quad 2$$

It is expressed in Norton equivalent form

$$I_{vR}=I_N-Y_{vR}V_{vR} \quad 3$$

The STATCOM voltage injection V_{vR} bound constraint is as follows:

$$V_{vR\min}\le V_{vR}\le V_{vR\max}$$

Where $V_{vR\min}$ and $V_{vR\max}$ are the STATCOM's minimum and maximum voltage.

The current expression in (3) is transformed into a power expression by the VSC and power injection into the bus k as shown in equations (4) and (5) respectively.

$$S_{vR}=V_{vR}I_{vR}^*=V_{vR}^2Y_{vR}^*-V_{vR}Y_{vR}^*V_k^* \quad 4$$

$$S_k=V_kI_{vR}^*=V_{vR}Y_{vR}^*V_k^*-V_k^2Y_{vR}^* \quad 5$$

Where $|V_{vR}|$ and δ_{vR} are the STATCOM voltage magnitude and angle, respectively.

Modelling of OPF

III. MATHEMATICAL FORMULATIONS OF OPTIMAL POWER FLOW PROBLEM

Mathematically, the OPF problem can be formulated as a nonlinearly constrained optimization problem can be expressed as follows.

$$\text{Minimize} \quad F(u,v)$$

$$\text{Subject to} \quad \begin{cases} E(u,v)=0 \\ I(u,v)\le 0 \end{cases}$$

Where F is the objective functions to be minimized, u and v are the vectors of dependent and control variables, respectively. F (u, v), objective function; E (u, v), set of equality constraints; I (u, v), set of inequality constraints.

u can be expressed as

$$u^T=[P_{G2}...P_{GNG},V_{G1}...V_{GNG},Q_{C1}...Q_{CNC},T_1...T_{NT}] \quad 6$$

Where NG, NT, and NC are the number of generators, the number of regulating transformers, and the number of VAR compensators, respectively.

The set of state variables for the OPF problem formulation are PG1, active power output at the slack bus, VL, voltage magnitude at PQ buses, load buses; QG, reactive power output of all generating units; Sl, transmission line loading (or line flow).

$$v^T=[P_{G1},V_{L1}...V_{LNL},Q_{G1}...Q_{GNC},S_{l1}...S_{\ln l}] \quad 7$$

The following equations give the objective function.

Cost minimization

$$F=\sum_{i=1}^{NG}(a_iP^2_{gi}+b_iP_{gi}+c_i)\$/h+penalty \quad 8$$

Voltage deviation (VD)

$$F=\sum_{i=1}^{NL}|V_i-1.0|+penalty \quad 9$$

Voltage stability index

$$L_j=\left|1-\sum_{i=1}^{ng}F_{ji}\frac{V_i}{V_j}\angle\theta_{ij}+\delta_i-\delta_j\right|+penalty \quad 10$$

Where θ_{ij} is the power factor angle and δ_i & δ_j are voltage angle of the ith and jth bus respectively

Active power loss

$$P_{loss(i)} = \sum_{\substack{j=1 \\ i \neq j}}^{nl} g_{i,j}(V_i^2 + V_j^2 - 2V_i.V_j \cos(\delta_i - \delta_j)) + penalty \qquad 11$$

Equality constraints

a) Real power constraints

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

b) Reactive power constraints

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

Inequality constraints

The inequality constraints can be considered the minimum and maximum values of Generators, Transformer, shunt var compensation, security or transmission line MVA rating, and STATCOM voltage magnitude, and angles. The voltage of each load bus must be restricted within its lower and upper operating limits. Line flow through each transmission line ought to be restricted by its capacity limits.

IV. ANALYTICAL HIERARCHY PROCESS METHOD

The Analytic Hierarchy Process (AHP) is widely used in multi-criteria decision-making tools for tackling multi-attribute decision-making problems in real situations [14]. It represents a powerful technique for solving complicated and unstructured issues that may have interactions and correlations among different objectives and goals [14],[15].

The mathematical modelling of the AHP methods can be:

Calculate the maximal Eigenvalue $\lambda_{\max}$ of the judgment matrix

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_j}{nW_i} \qquad 12$$

Where $(AW)_j$ represents the jth element in vector AW

The consistency index of a hierarchy ranking *CI* is defined as

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad 13$$

Where $\lambda_{\max}$ the maximal Eigenvalue of the judgment matrix is *n* the dimension of the judgment matrix.

The stochastic consistency ratio is defined as

$$CR = \frac{CI}{RI} \qquad 14$$

Where *RI* is a set of given average stochastic consistency, indices and *CR* is the stochastic consistency ratio.

For matrices with dimensions ranging from one to nine, respectively, the values of RI have been displayed in [16],[15].

It is evident that for a matrix with a dimension of one or two, it is not necessary to check the stochastic consistency ratio. Generally, the judgment matrix is satisfied (acceptable) if the stochastic consistency ratio, *CR* < 0.10.

V. OVERVIEW OF OPTIMIZATION ALGORITHMS

Teaching Learning Based Optimization

The TLBO algorithm is a teaching-learning process motivated algorithm proposed by Rao et al and Savsani based on the impact of a teacher on the output of learners in a class [17], [18].

The algorithm describes two basic modes of learning:

(i) Teacher phase

(ii) Learner phase

i. Teachers phase

a group of learners is considered as population and different subjects offered to the learners are considered as other design variables of the optimization problem and a learner's result is analogous to the 'fitness' value of the optimization problem. The best solution in the entire population is considered as the teacher. The design variables are the parameters involved in the objective function of the given optimization problem, and the best solution is the best value of the objective function.

In TLBO, at each iteration, the mean of decision vectors is computed and denoted by M, the student with the best mark is designated as a teacher. Then, the position of all students is updated via the following equation [16], [18].

$$X_{i,new} = X_{i,old} + r(X_{teacher} - T_F.M) \qquad 15$$

ii. Learner phase

As in a real classroom, students learn from each other by discussions, presentations and formal communications; in student phase, for each student i, another student j is randomly picked up, and then, the student with better mark (fitness) is attracted towards (learns from) the other student. That is if student j is fitter than student i, then

$$X_{i,new} = X_{i,old} + ri(X_j - X_{i,old}) \qquad 16$$

JAYA algorithm

The Jaya algorithm is a met heuristic which is capable of solving both constrained and unconstrained optimization problems. It is a population-based method which repeatedly modifies a population of individual solutions [19].

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}[(X_{j,best,i}) - (|X_{j,k,i}|)] - r_{2,j,i}[(X_{j,worst,i}) - (|X_{j,k,i}|)] \qquad 17$$

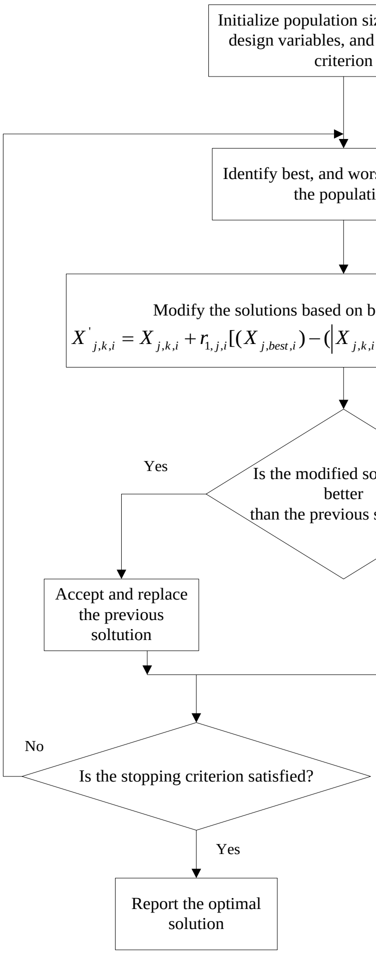

Figure 3. Flow chart of Jaya algorithm

Proposed Multi Population-Based Modified Jaya (MPMJ) Algorithm

In the proposed modified JAYA algorithm, an elite member in the population act as a guide to other members in the population to enhance their positions to a place near to the best-known position.

For the proposed modified Jaya algorithm, the mathematical equation can be shown in equation (18) below [20].

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}[(X_{j,worst,i}) - (|X_{j,k,i}|)] - L * r_{2,j,i}[(|X_{j,k,i}|^2) - (X_{j,best,i})] \tag{18}$$

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.

Figure 4, the algorithm steps for the multi-population algorithm can be explained

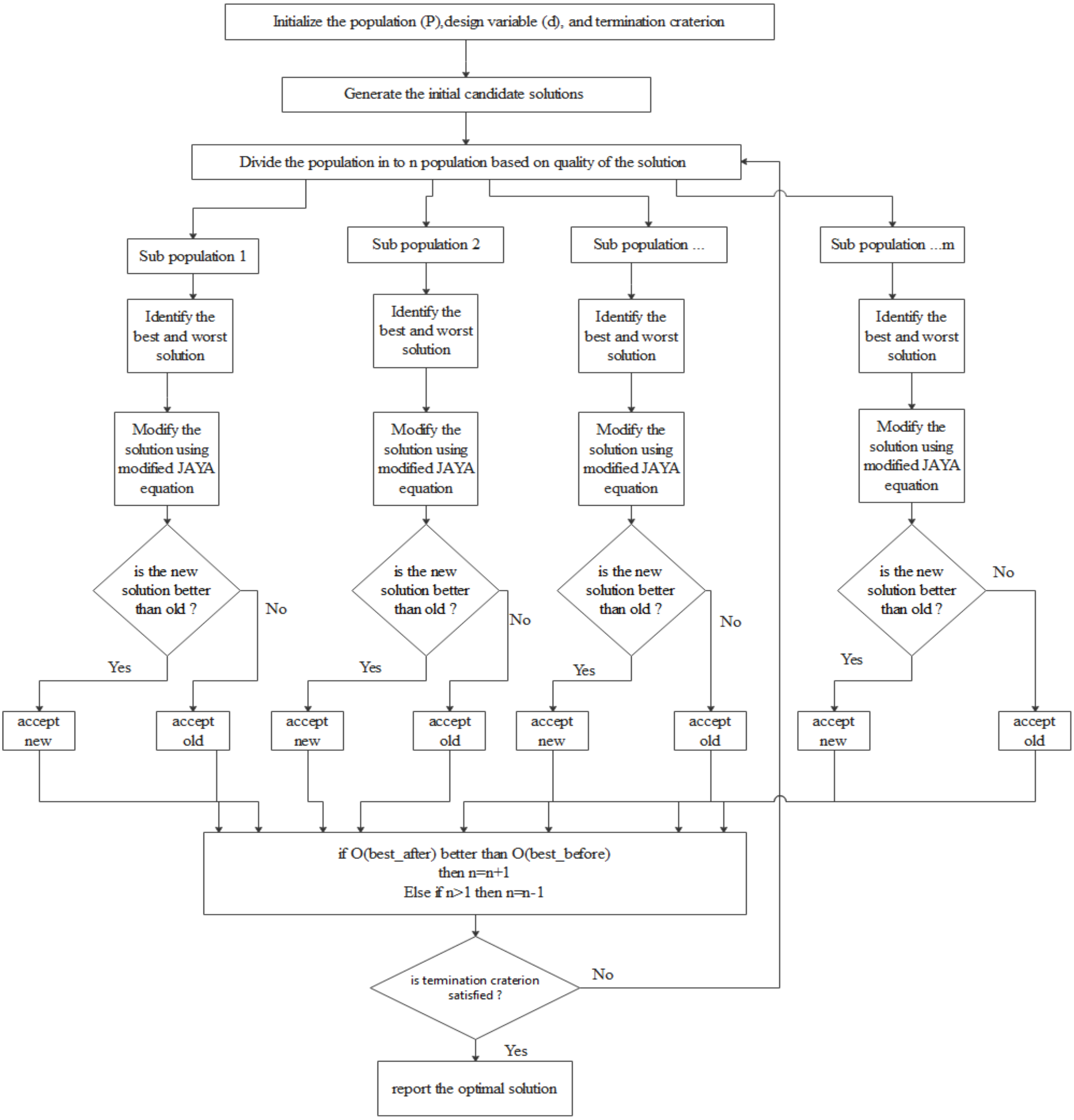

Figure 4. The basic flow chart of the MPMJ algorithm

In the following Figure 5, the application of the multi population based modified Jaya (MPMJ) algorithm for the solution of optimal power flow without and with STATCOM device.

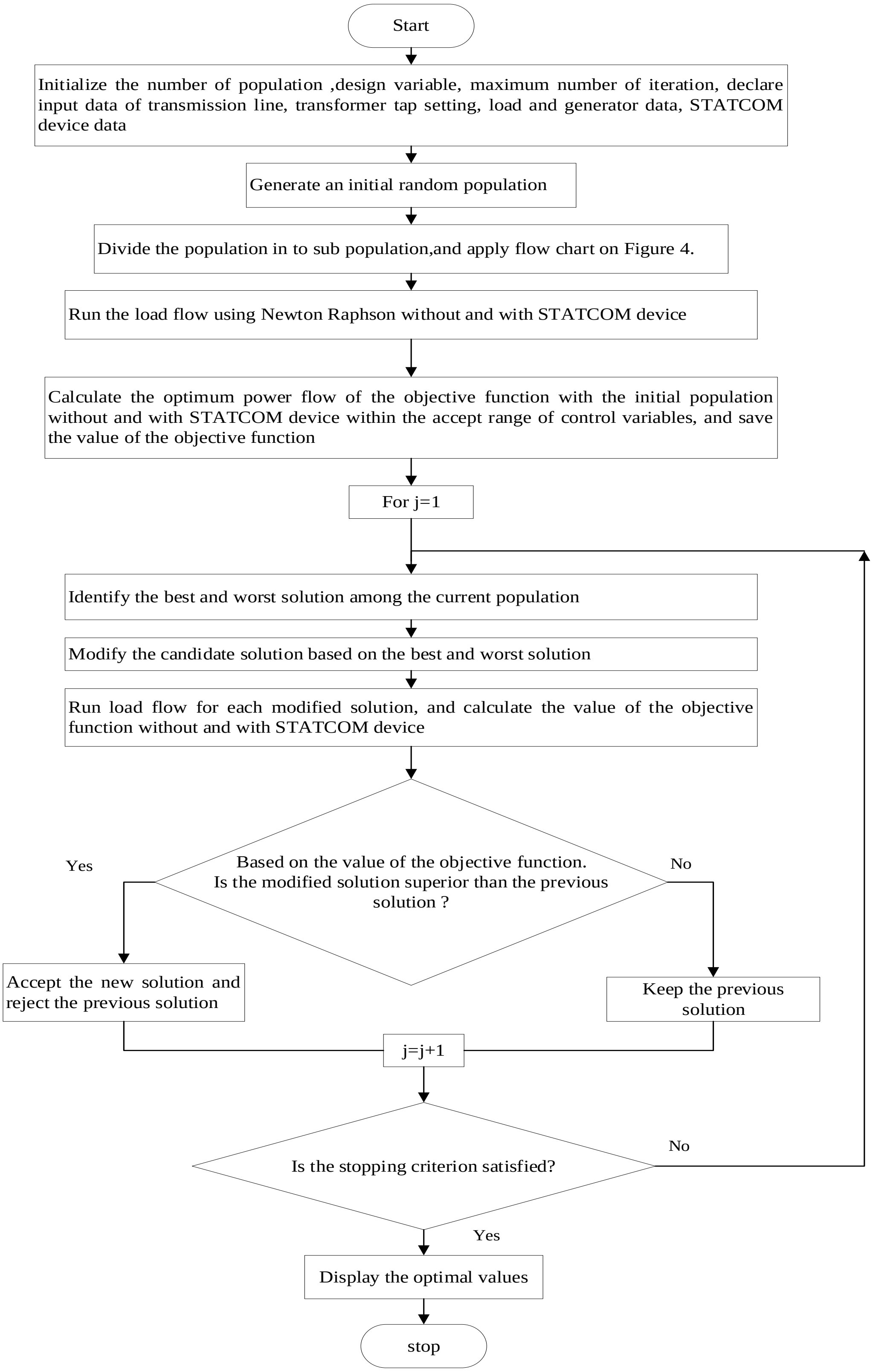

Figure 5. Flow chart of MPMJ algorithm for the application of optimum power flow solution without and with STATCOM device

VI. RESULT AND DISCUSSION

The effectiveness of the metaheuristic Algorithm TLBO, JAYA, and proposed Multi population Modified-based Jaya (MPMJ) Algorithm without, and with STATCOM device are examined on standard IEEE-30, bus system to test the system for OPF problems. The optimal allocation of the STATCOM device is selected by using the Analytical Hierarchy Process (AHP) method. The voltage magnitude and phase angle of the STATCOM device are 0.9 to 1.1pu, and -10 to 10 degree, respectively [21].

The case studies for simulation are as follows under normal operating conditions:

Case I: Single-objective optimization without STATCOM device

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

Case I: Single-objective optimization without STATCOM device

In this section, the proposed comparison techniques of optimal power flow solutions are evaluated using the IEEE-30 bus system.

Figure 6(a) shows the convergence characteristics of the fuel cost of generation for the IEEE 30-bus test system under normal operating conditions without STATCOM device. The minimum costs obtained using TLBO, JAYA, and proposed MPMJ algorithms are798.79$/hr, 797.8$/hr, and 797.5$/hr, respectively. Figure 6(b) shows the convergence characteristics of total real power loss for the IEEE 30-bus system under normal operating conditions. The minimum power losses obtained using TLBO, JAYA, and proposed MPMJ algorithms are 0.046p.u, 0.0288p.u and 0.0286pu respectively. Figure 6(c) shows the convergence characteristics of the sum of voltage deviation for IEEE 30-bus system under normal operating conditions. The minimum sum of voltage deviation obtained using TLBO, JAYA, and proposed MPMJ algorithms are 0.203084p.u, 0.1133pu and0.0987pu, respectively. Figure 6(d) shows the convergence characteristics of the voltage stability index for the IEEE 30-bus system under normal operating conditions.

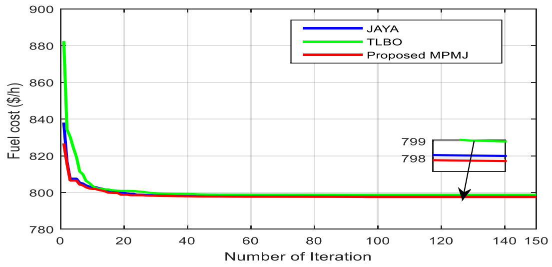

Figure 6(a). Convergence characteristics of total fuel cost of generation without STATCOM device

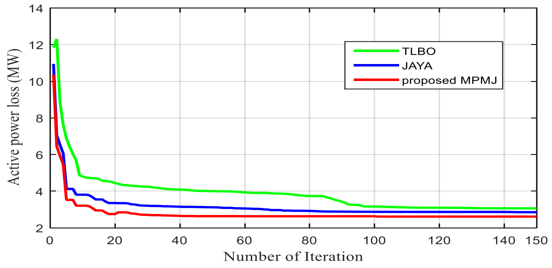

Figure 6 (b). Convergence characteristics of total active power loss without STATCOM device

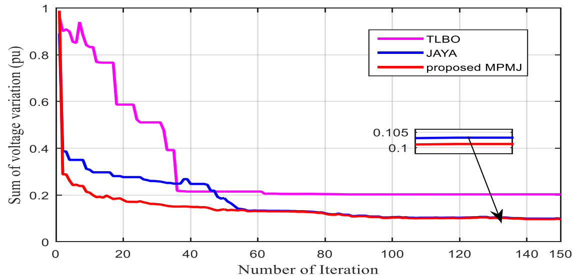

Figure 6 (c). Convergence characteristics of the voltage deviation without STATCOM device

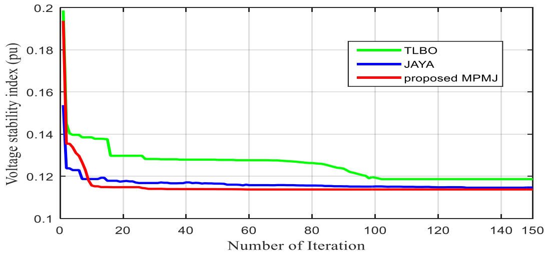

Figure 6(d). Convergence characteristics of the sum of squared voltage stability index without STATCOM device

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

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.

The considered locations of STATCOM are the bus numbers 19,24,26,29, and 30. These locations are taken based on the first five maximum voltage stability index of load buses from steady-state values of load buses. The value of the voltage stability index at bus 19,24,26,29, and 30. is 0.0621, 0.0690, 0.0812, 0.0697, and 0.0822 respectively. The voltage stability index for load buses is shown in Figure 7.

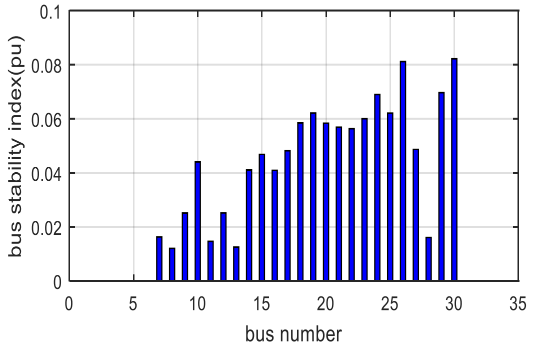

Figure 7. Bus stability index for IEEE-30 bus system

Table 1 gives the optimized values of different attributes at different alternatives. This OPF results with the STATCOM device are used as a decision matrix for the system and then given as an input to the AHP method.

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.

Table 3 is a normalized principal eigenvector called a priority vector or weight matrix of the attributes. Since it is normalized, the sum of all attributes in the priority vector is 1, and the Priority vector shows relative weights among the things that we compare.

Table 4 shows the relative ranking of alternatives under five objective functions, which are the minimization of fuel cost of the generator, minimizing the sum of voltage deviation, minimizing active power loss, and enhancement of voltage stability index by the AHP method.

Table 1. OPF results and decision table for the AHP method for IEEE-30 bus

Alternatives	Attributes			
Load bus	Fuel cost ($/h)	Power loss (pu)	VSI	VD (pu)
Bus 19	797.47	0.0252	0.1023	0.0970
Bus 24	797.34	0.0280	0.1031	0.096
Bus 26	797.3	0.0265	0.1016	0.0924
Bus 29	797.2	0.0285	0.1040	0.0990
Bus 30	797.3	0.0272	0.1020	0.0918

Table 2. Pairwise comparison matrix for attributes

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

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

Alternatives load bus	AHP ranking
Bus 19	2
Bus 24	5
Bus 26	1
Bus 29	3
Bus 30	4

Figures 8(a)-8(d) show the convergence characteristic of each objective function with STATCOM at bus 26 for IEEE-30 bus system, showing smooth convergence to the optimum value without spontaneous oscillations for best run under normal operating conditions.

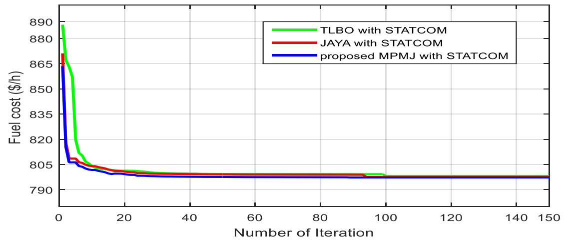

Figure 8(a). Convergence characteristics of total fuel cost of the generator using STATCOM at bus 26

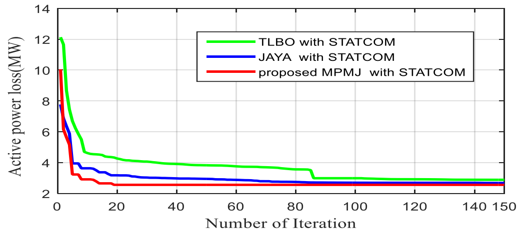

Figure 8(b). Convergence characteristics of real power loss using STATCOM at bus 26

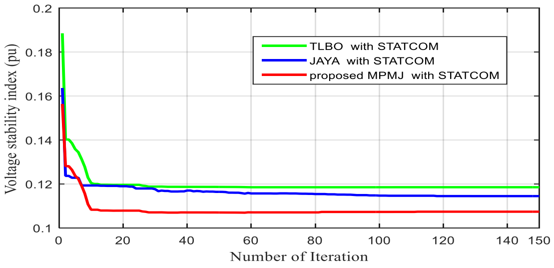

Figure8(c). Convergence characteristics of sum of squared voltage stability index with STATCOM at bus 26

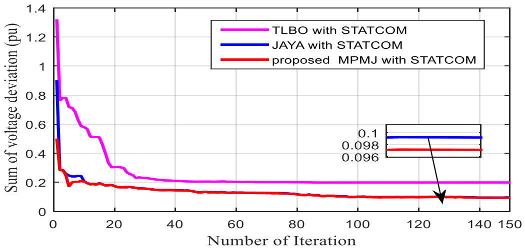

Figure 8(d). Convergence characteristics of voltage deviation using STATCOM at bus 26

VII. CONCLUSION

The optimal power flow solution is the critical power system network resources, and various optimization strategies exist to solve the optimal power flow problems. In this paper, we applied the proposed MPMJ algorithm without and with STATCOM device, compared to the recent literature algorithm Results from the proposed algorithm method are contrasted with the recent literature in Table 5. From the result, it is clear that the proposed method can achieve better results concerning other algorithms for IEEE-30 bus test system. These values are not negligible because of the continuous operations of power dispatch throughout the years.

Table 5. Comparison of proposed MPMJ algorithm with other recent methods reported in the literature

Algorithms	Fuel cost of the generation ($/h)	Active power loss (MW)	Voltage deviation (VD)pu	Voltage stability index
GWO [22]	799.558	2.9435	0.11873	NR
DE [23]	801.23	3.38	NR	NR
EGA [24]	800.083	3.244	NR	0.1303
ABC [10]	800.660	3.1078	NR	NR
MSA [25]	800.509	3.1005	0.1084	0.1371
MFO [26]	799.072	2.853	0.1065	0.1138
MSCA [27]	799.31	2.9334	0.1031	NR
SCA [27]	800.1	9.06	0.1082	NR
MSLFA [28]	802.258	3.8239	NR	NR
SSOA [28]	799.762	2.9454	NR	NR
PSO [29]	NR	3.70	NR	NR
JAYA [30]	800.47	9.06	0.1273	NR
Gradient method [31]	804.85	10.48	NR	NR
AGA-POP [32]	799.84	8.916	NR	NR
Proposed MPMJ	**797.5**	**2.6119**	**0.0987**	**0.1127**

The only parameters to be set for TLBO and JAYA algorithms are population size, several iterations and number of runs, the only difference for proposed MPMJ algorithms is the number of initial sub-population and modified original JAYA algorithm. The optimal values of the proposed MPMJ algorithm are converged early, including the STATCOM device, and optimal values are obtained for the objective function of generation fuel cost, active power loss, minimizing voltage summation and enhancing voltage stability index.

The proposed MPMJ algorithm is constructed using the exclusive collection of best group values and subpopulations. The key benefit of the proposed MPMJ algorithm to solve the OPF problem is that there is no tuning parameter and simple divergence control. Therefore, due to not using external settings, the result obtained is more desirable than the other metaheuristic algorithm. Thus, the proposed MPMJ algorithm can be easily extended to solve the OPF problem with a quick convergence rate and the optimal result in the power system operating limits.

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