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# A Novel Modified Lightning Attachment Procedure Optimization Technique for Optimal Allocation of the FACTS Devices in Power Systems

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**ABSTRACT** The Flexible AC Transmission Systems (FACTS) are the static power electronic devices that are installed and used in AC transmission networks to enhance the capability of transferring the power for providing the controllability and stability. However, the optimization of site and size of these devices is a crucial task due to their high capital cost and practical capabilities. In this paper, the optimal reactive power dispatch (ORPD) embedded with two effective controllers including the Static VAR Compensator (SVC) and Thyristor Control Series Capacitor (TCSC) is solved using a Modified Lightning Attachment Procedure Optimizer (MLAPO). The searching capability of basic LAPO is enhanced and the stagnation of basic LAPO is avoided by application of levy flight distribution and spiral orientation motion. The optimization for these devices is for reducing the power losses, voltage deviations, and the operating cost. MLAPO is examined and tested on modified IEEE30 and IEEE57 bus-standards considering SVC and TCSC. The effectiveness of MLAPO is further analyzed and compared with the outcomes of the well-known optimization techniques namely LAPO, PSO, ALO, EO, MPA, WOA and SCA with and without FACTS devices.

**INDEX TERMS** Flexible AC transmission systems, optimal power flow, lightning attachment procedure optimization, thyristor control series capacitor, static VAR compensator.

## NOMENCLATURE

| | | |
|---|---|---|
| $G_K$ | : | Conductance of branch K |
| $V_m, V_n$ | : | Voltage Magnitudes |
| $N_B, N_T$ | : | No. of buses and transformers tap settings |
| $P_{Gm}, P_{Dm}$ | : | Active power injected and demand at bus "m" |
| $Q_{Gm}, Q_{Dm}$ | : | Reactive power injected and demand at bus "m" |
| $N_{SVC}$ | : | No. of SVC |
| $N_{TCSC}$ | : | No. of TCSC |
| $N_c$ | : | No. of Shunt Compensators |
| $NL$ | : | Number of transmission lines |
| $N_{PV}$ | : | No. of Generators |
| $N_{PQ}$ | : | No. of load buses |
| $G_{mn}$ | : | Conductance |
| $B_{mn}$ | : | Susceptance |

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## I. INTRODUCTION

### A. GENERAL

The electric power networks are very complex and allied to the numerous generators, transformers, variety of loads and transmission lines to supply the power for the utilities. The burden of electric power networks becomes heavier due to increment of the load demand which can cause instability and lead to transmission limits factor [1]. This power instability can be reduced via applications of advance controlled technology such as Flexible AC Transmission Systems (FACTS). In an associated power network, FACTS devices are providing the new opportunity of minimizing power losses and the line power flow, whereas sustaining the bus voltages within their permissible perimeters. The effective reactive power scheduling at weak buses of electric power system is helpful to reduce the active power losses as well as improve the voltage profile of the overall power network [2].

In addition, the FACTS devices aim to control voltage, impedance and phase angle of the high voltage AC lines and improve the power system stability [3]. The Thyristor Controlled Series Compensation (TCSC) and Static VAR Compensator (SVC) are the members of FACTS devices and mostly used in the power system for stabilizing the operation. TCSC controls the power flow in line and damps the power system oscillations, which further improves the voltage stability, transfer capability and reactive power demand. While, SVC controls the power in line, improves system voltages and damps power system oscillations that can improve overall transient stability of electrical system [4].

### B. LITERATURE REVIEW

The optimal reactive power dispatch (ORPD) is generally considered as a nonlinear issue related to optimal power flow problem. In last few decades, there were many classical techniques which are used to solve the ORPD problem, such as interior point method, nonlinear and linear programing, gradient-based approach, quadratic programming techniques, Newton method, dynamic programing, and Langrangian technique, respectively [5]–[12]. But these optimization techniques have faced some limitations, such as handling of inequality constraints and nonlinear discontinuous functions, loss of accuracy, trapped into local minima, complexity, premature convergence, etc. Thus, these optimization techniques are not appropriate to solve the ORPD with FACTS allocation issues. To resolve the hard problems, the new optimization techniques were later introduced, such as evolutionary programming (EP), genetic algorithm (GA), whale optimization algorithm (WOA), binary bat algorithm (BBA), firefly algorithm (FA), enhanced leader particle swarm optimization (ELPSO), grey wolf optimizer (GWO), sine cosine algorithm (SCA), marine predator algorithm (MPA) and lightning attachment procedure optimizer (LAPO) [13]–[22]. These optimization techniques have applied efficiently in the power system.

In the literature, the optimal location and setting of FACTS devices attract universal scholars in power systems, wherever numerous approaches as well as standards are used in this field. Jordehi [23] presented an imperialistic competitive algorithm (ICA) for resolving complex optimization problems in different fields. The suggested technique is used to optimally assign the FACTS devices to improve safety. Considering an optimal setting and employment of FACTS controller, Safari *et al.* [24] adopted strength pareto multi-objective evolutionary algorithm to decrease the stability concerns. This technique approves the efficiency of the recommended method which is feasible for resolving the combinatorial problems of FACTS devices position and site in large scale scheme.

Shafik *et al.* [25] proposed an adaptive parallel seeker optimization algorithm (APSOA) which is employed to solve the multi-objective problem of OPF for minimizing the installation cost using SVC and TCSC. On the way to test the dominance, this method was applied to different IEEE bus standards, such as 9, 30 and 57-bus system at contingency and normal operating condition. Singh *et al.* [26] offered mixed integer linear programming (MILP) to find the optimal settings and locations of Thyristors Control Phase Shifter (TCPST). Nguyen and Mohammadi [27] designed MINLP approach for the optimal appointment of TCSC in the power system. Mahad *et al.* [28] established corresponding dynamic strategy-based fast decomposed GA to discover the optimal position of the SVC for diminishing the fuel cost, voltage deviation as well as the reactive power destruction. The recommended technique was executed on IEEE30-bus and IEEE 118-bus test schemes. A harmony search algorithm (HSA) is discussed by Sirjani, et.al in [29] for concurrent minimization of the total cost and voltage profile as well as improving the voltage stability index using IEEE 57-bus test system by means of shunt capacitors, SVC and Static Synchronous Compensators (STATCOM). Agrawal *et al.* [30] discussed the population-based evolutionary optimization technique of TLBO for optimizing size and location of TCSC. The installation cost of TCSC and voltage deviation are minimized using IEEE 14, 30 and Indian 75 bus system [30]. Roy, et.al. [31] proposed artificial bee colony (ABC) and biogeography-based optimization (BBO) techniques to minimize the operation cost with optimal allocation of TCSC and TCPS using IEEE 30-bus standard. Dutta, et.al [32] presented an efficient quasi-oppositional chemical reaction optimization (QOCRO) applied to multi-objective ORPD problem with FACTS devices according to IEEE 14 and 30-bus standard. A graphical user interface (GUI) based-on genetic algorithm (GA) was proposed by Ghahremani, et.al [33] to improve the system static load aptitude, voltage stability and security, minimize power losses by means of using different categories of FACTS devices, such as UPFC, TCPST, TCVR, TCSC and SVC, respectively. Sebaa, et.al [34] proposed a tuning and location method for multiple FACTS devices to optimize the OPF problem by applying cross-entropy (CE) techniques based on IEEE 30-bus standard. Benabid, et.al [35] proposed a novel non-dominated sorting PSO (NSPSO) technique to address the setting and optimal location of TCSC and SVC for minimizing the voltage deviation and power losses as well as enhancing the voltage stability using IEEE 30 and Algerian 114-bus system. Dutta *et al.* [36] proposed hybridization of DE with CRO (DE/CRO) technique to solve the parameter setting and the optimal placement of TCSC and SVC according to IEEE 30-bus system. Sode-Yome *et al.* [37] proposed an appropriate choice of FACTS devices to enhance the static voltage stability and the loading margin. Muhammad, et. al [38] proposed Shannon entropy-based diversity in PSO dynamic, i.e., FOPSO-EE to minimize power losses, voltage deviation and overall cost using FACTS devices in IEEE 30-bus system.

LAPO is an efficient optimization technique, proposed by Nematollahi et.al. [39], [40]. LAPO imitates the lightning procedure which has been applied to various optimization issues. Taher, et.al [41] used LAPO technique to find best optimal position and sizing UPFC controller in transmission system. Youssef, et.al [42] solved OPF problem using LAPO technique. Hashemian, et.al [43] assigned the optimal placement and ratings of DGs in distributed grid using LAPO. Liu, et. al [44] optimize the image segmentation using LAPO technique. The conventional LAPO may apt to trap into the local optima, so a modified MLAPO is proposed to solve the stagnation of LAPO.

### C. CONTRIBUTION TO THE RESEARCH

In this research, the novel modified MLAPO technique is used to solve the ORPD problem with optimal allocation and FACTS devices to minimize the power losses, voltage deviation and the operational cost using IEEE 30 and 57-bus standards. The salient features of this study are discussed as follows.

1) A novel modified MLAPO containing spiral drive and levy flights is proposed to enhance the searching ability of the algorithm.
2) To validate the performance of MLAPO, the simulations are performed and compared with different optimization techniques, such as conventional LAPO, PSO, ALO, EO, MPA, WOA and SCA, respectively.
3) MLAPO is applied to IEEE 30 and 57-bus standards with and without optimal allocations of the TCSC and SVC controllers to minimize power losses, voltage deviation and operating cost.

The utilization of MATPOWER is applied to ensure that detailed outcomes can be achieved by running the Load Flow Analysis (LFA). The rest of the paper is set as follows. Section II formulates the fitness objectives of ORPD, Section III represent the optimal allocation of TCSC and SVC. Section IV provides the novel implementation of modified MLAPO technique. Section V gives simulation results and discussion, while Section VI summarizes the conclusions.

## II. PROBLEM FORMULATION

### A. MINIMIZATION OF POWER LOSSES

For reduction in power line losses, the following expression can be used.

$$F_1(z_1, z_2) = \sum_{R=1}^{NL} G_R \left[ V_m^2 + V_n^2 - 2V_m V_n \cos(\delta_{mn}) \right] \quad (1)$$

Here, $z_1$ is the dependent variables of reactive power generators, load voltages and the transmission line loadings.

$$z_1 = \left[ Q_{G1}, \ldots, Q_{GN_{PV}}, V_{L1}, \ldots, V_{LN_{PQ}}, S_{L1}, \ldots, S_{LN_L} \right] \quad (2)$$

While, $z_2$ is the vector of control variables which consisting of reactive power injections, magnitudes of generators, transformer tap settings, SVC and TCSC.

$$z_2 = \begin{bmatrix} T_1, \ldots, T_{N_T}, V_{G1}, \ldots, V_{GN_{PV}}, Q_{C1}, \ldots, Q_{CN_C} \\ SVC_1, \ldots, SVC_{KNVC}, TCSC_1, \ldots, TCSC_{NTCSC} \end{bmatrix} \quad (3)$$

The equality and inequality constraints must be satisfied. The expression related to equality constraints are defined as:

$$P_{Gm} - P_{Dm} - V_m \sum_{N=1}^{N_B} V_n \begin{bmatrix} B_{mn} sin\,(\delta_{mn}) + \\ G_{mn} cos\,(\delta_{mn}) \end{bmatrix} = 0 \quad (4)$$

$$P_{Gm} - P_{Dm} - V_m \sum_{N=1}^{N_B} V_n \begin{bmatrix} B_{mn} cos\,(\delta_{mn}) + \\ G_{mn} sin\,(\delta_{mn}) \end{bmatrix} = 0 \quad (5)$$

While, the inequality constraints are defined as:

$$T_i^{min} \leq T_i \leq T_i^{max} \quad i = 1, 2, \ldots, N_T \quad (6)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i = 1, 2, \ldots, N_B \quad (7)$$

$$Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max} \quad i = 1, 2, \ldots, N_{PV} \quad (8)$$

Eq. (9) represents the limits of the shunt reactive VAR compensators.

$$Q_{C_i}^{min} \leq Q_{C_i} \leq Q_{C_i}^{max} \quad i = 1, 2, \ldots, N_C \quad (9)$$

Eq. (10) and (11) are the limits of the FACTS devices using *TCSC* and *SVC*.

$$SVC_i^{min} \leq SVC_i \leq SVC_i^{max} \quad i = 1, 2, 3, \ldots, N_{SVC} \quad (10)$$

$$TCSC_i^{min} \leq TCSC_i \leq TCSC_i^{max} \quad i = 1, 2, 3, \ldots, N_{SVC} \quad (11)$$

### B. MINIMIZATION OF VOLTAGE DEVIATION

To minimize the voltage deviation, the following expression can be used.

$$min = F_2 = VD = \sum_{i=1}^{Nb} |V_b - 1.0| \quad (12)$$

### C. MINIMIZATION OF COST USING FACTS DEVICES

To minimize the overall cost, the FACTS devices are expressed as follows.

$$min = f_3 = C_{TOTAL} = C_{ENERGY} + C_{FACTS} \quad (13)$$

Here,

$$C_{ENERGY} = 1000 \times 0.06 \times 365 \times 24 \times P_{losses} \quad (14)$$

Here, 365 are the days in a year, 24 is the number of hours in a day, 0.06 is the cost associated with the power losses measure in \$/KWhr and 1000 (\$) is the fixed installed cost of the shunt capacitor. While, the cost of the $C_{FACTS}$ are computed by Siemens *AG* database as follows [2].

$$C_{FACTS} = \alpha s^2 + \beta s + \gamma \quad (15)$$

here, $\alpha, \beta$ and $\gamma$ are the cost coefficients of the FACTS devices and depend on the type of the FACTS. $C_{FACTS}$

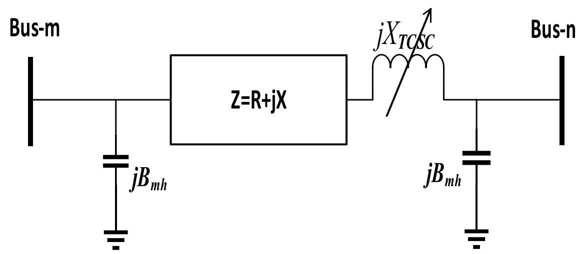


**FIGURE 1.** Simplified model of TCSC.

is the cost of FACTS devices and its value measured in $US\,\$/kVar$ while 's' is the operating range of the FACTS devices in $MVar$. The cost functions for $TCSC$ and $SVC$ can be expressed as follows [2].

$$C_{TCSC} = 0.0015\,(s)^2 - 0.7130(s) + 153.75\,(US\$/kVar) \quad (16)$$

$$C_{SVC} = 0.0003\,(s)^2 - 0.3051\,(s) + 127.38\,(US\$/kVar) \quad (17)$$

## III. STEADY STATE MODEL OF FACTS

### A. MODELLING OF TCSC

The series compensator TCSC is a static reactor/capacitor with impedance $jX_c$ reactor/capacitor. Hence, it can vary the impedance to above or below the line natural impedance. The static model of the network with TCSC connected between branches ($m$ to $n$) are given in Fig. 1. The active and reactive power expressions are given in Eq. (18) and (19) and represent the optimal TCSC between the two branches namely $m$ and $n$. The expression related active and reactive power flows from branch $m$ to $n$ are given as follows.

$$P_{mn} = V_m^2 G_{mn} - V_m V_n G_{mn} cos\,(\delta_m - \delta_n) - V_m V_n B_{mn} sin\,(\delta_m - \delta_n) \quad (18)$$

$$Q_{mn} = -V_m^2 B_{mn} - V_m V_n G_{mn} sin\,(\delta_m - \delta_n) + V_m V_n B_{mn} sin\,(\delta_m - \delta_n) \quad (19)$$

The active and the reactive power flows between branches $n$ to $m$ are given as follows.

$$P_{nm} = V_n^2 G_{nm} - V_n V_m G_{nm} cos\,(\delta_n - \delta_m) - V_n V_m B_{nm} sin\,(\delta_n - \delta_m) \quad (20)$$

$$Q_{nm} = -V_n^2 B_{nm} - V_n V_m G_{nm} sin\,(\delta_n - \delta_m) + V_n V_m B_{nm} sin\,(\delta_n - \delta_m) \quad (21)$$

Here, the conductance and the susceptance of the transmission lines are given as follows:

$$G_{mn} = \frac{R}{R^2 + (X - X_{TCSC})^2} \quad (22)$$

$$B_{mn} = \frac{-X - X_{TCSC}}{R^2 + (X - X_{TCSC})^2} \quad (23)$$

### B. MODELLING OF SVC

The simplified model of SVC controller connected to the transmission line by switching several combinations of inductors/capacitors parallelly with the lines given in Fig. 2.

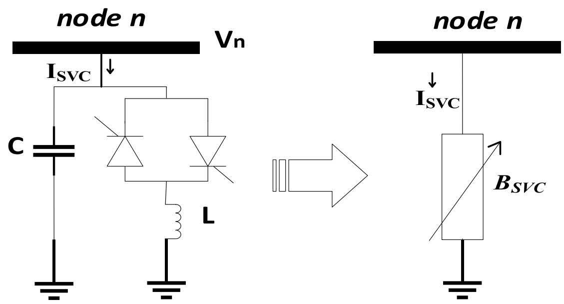


**FIGURE 2.** Simplified model of SVC.

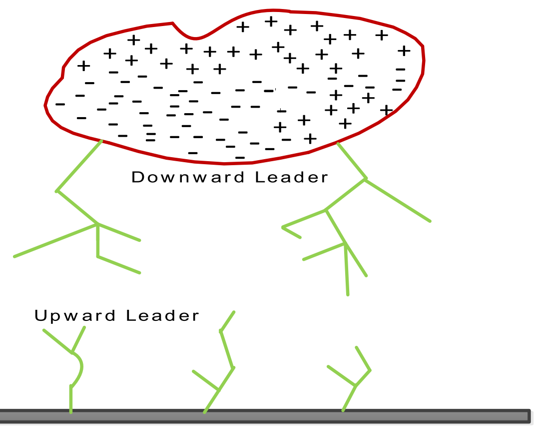


**FIGURE 3.** Formation of the charges and leaders in the cloud.

The equivalent circuit of SVC can be modelled as shunt connected variable susceptance $B_{svc}$ at bus $n$. The reactive power injected into bus due to SVC is as follows:

$$Q_{svc} = B_{svc} \times V^2 \quad (24)$$

where, $V$ is the magnitude of the voltages of the bus at which SVC is connected.

## IV. METHODOLOGY

In this section, the novel modified LAPO technique is represented with its graphical representation in Fig. 4 in order to solve the ORPD problem with optimal allocation of FACTS devices containing TCSC and SVC, respectively.

### A. COVENTIONAL LAPO ALGORITHM

The LAPO technique is followed the mechanism of lightning phenomena in which there are four steps are considered, such as ascending and descending leaders' arrangements, breakdown of air on cloud surface and strike point.

Fig. 3 demonstrates the development of charges in clouds, where the huge number of negative charges with less positive charges appear at the bottom of the cloud while huge positive charges appear on the top of the cloud. As the quantity of the charges are increasing, it can cause occurrence of the breakdown inside the could whereas the voltage increases at the clouds edge. The gesture of lightning will happen in different stages, where it stops after each step. When the lightnings move towards the ground or in several directions,

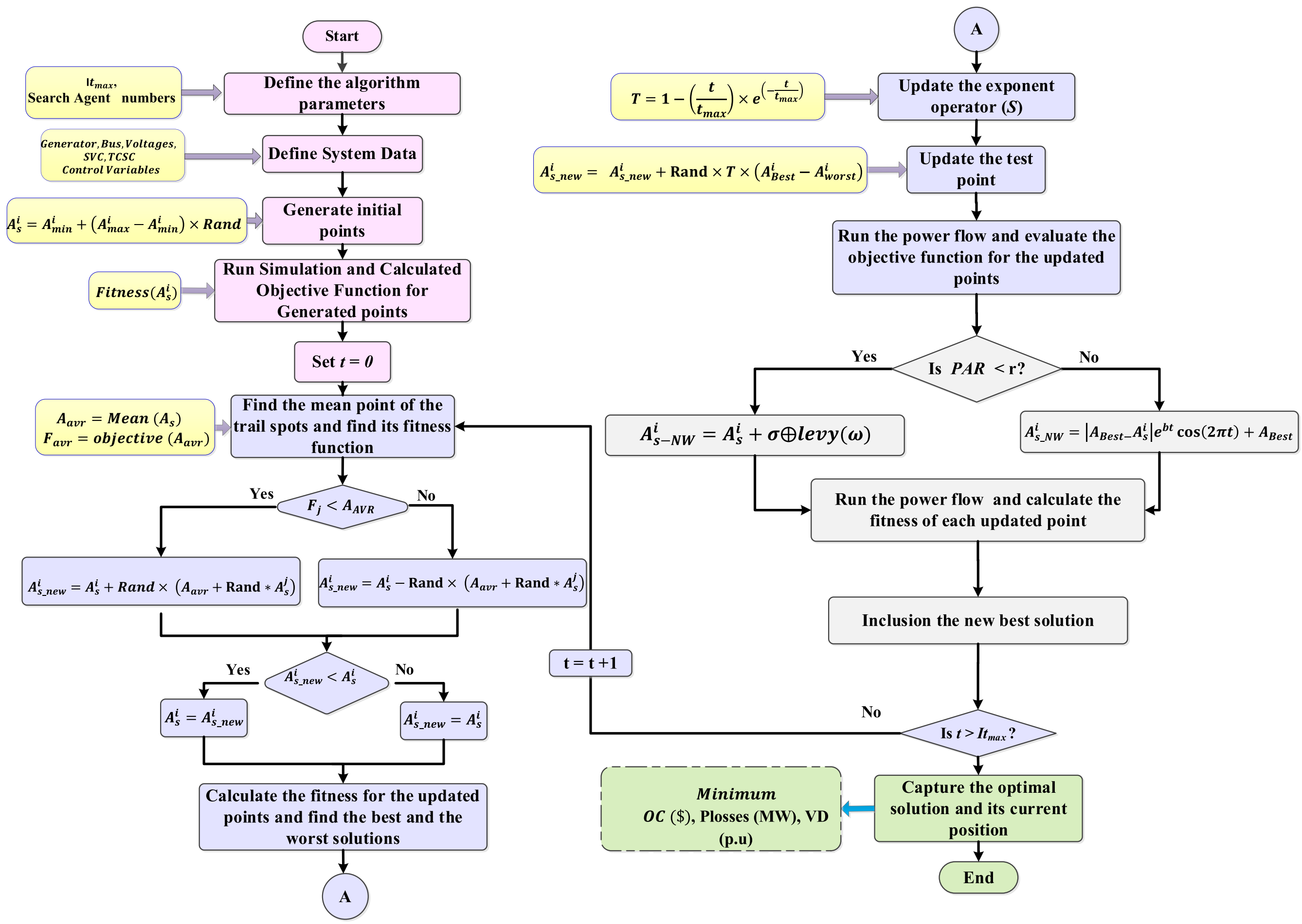


**FIGURE 4.** Modified LAPO Algorithm for ORPD solution with optimal allocations of FACTS tested on IEEE30 and IEEE57 bus standards.

they can be called as downward leaders. Due to accumulation, the enormous carriers of negative charges appear at the bottom of the cloud whereas the positive charges will appear at the sharp points on the ground which can increase in charges, upward leader developed from ground and air breakdown.

### 1) INITIALIZATION

In the initialization process, the agents of the initial search space of upward leaders can be defined as follows.

$$A_s^i = A_{min}^i + (A_{max}^i - A_{min}^i) \times Rand \tag{25}$$

The objective function can be defined as follows.

$$F_s^i = Objective(A_s^i) \tag{26}$$

### 2) NEXT JUMP DETERMINATION

The crossponding fitness and average points can be expressed in Eq (27) and (28), given as follows.

$$F_{avr} = Objective(A_{avr}) \tag{27}$$

$$A_{avr} = Mean(A_s) \tag{28}$$

In process of updating location of agents, another agent randomly $j$, where $i \neq j$ is selected and compared the value with average value of the agent, is expressed as follows.

$$When, f\left(A_s^j\right) > f\left(A_{avr}\right)$$

$$A_{s\_Nw}^i = A_s^i + Rand \times (A_{avr} + Rand \times A_s^j) \tag{29}$$

$$When, f\left(A_s^j\right) < f\left(A_{avr}\right)$$

$$A_{s\_Nw}^i = A_s^i - Rand \times (A_{avr} + Rand \times A_s^j) \tag{30}$$

### 3) BRANCH VANISHING

The mean acceptance of the new agents can cause vanishing of the branch. So, the new objective can be achieved by the following expression.

$$\begin{aligned} A_s^i &= A_{s\_Nw}^i \quad if\ F_{s-Nw}^i < F_s^i \\ A_{s-Nw}^i &= A_s^i \quad otherwise \end{aligned} \tag{31}$$

### 4) UPWARD LEADER MOVEMENT

Formulas (32) and (33) represents the movement of the entire upward agents. Whereas, the positioning of upward leaders follows the downward leader and can be controlled by the exponential operator via the channel, which is expressed as follows.

$$A^i_{sNW} = A^i_{s\_Nw} + Rand \times T \times (A_{Best} - A_{worst}) \quad (32)$$

$$T = 1 - \left(\frac{t}{t_{max}}\right) \times exp\left(-\frac{t}{t_{max}}\right) \quad (33)$$

Here, $A_{Best}$ and $A_{worst}$ are representing the best and worst solution.

#### 5) STRIKE POINT

The lightning mechanism will stop when striking point is determined and upward/downward leaders meet each other. The algorithm stops when the convergence criterion is satisfied.

### B. MODIFIED MLAPO ALGORITHM

The novel modified LAPO technique depends on the search ability of traditional LAPO technique by improving its exploration and exploitation phases. In the exploration phase, updating the placement of test points or agents using the random Levy flights, the expression is as follows.

$$A^i_{s-NW} = A^i_s + \sigma \oplus levy(\omega) \quad (34)$$

Here, the step size is represented by term operator '$\sigma$' and can be taken from the flowing equation.

$$\sigma \oplus levy(\omega) \sim 0.01\frac{u}{|v|^{1/\omega}}\left(A^i_s - A_{Best}\right) \quad (35)$$

Here, the values of operators '$v$' and '$u$' are taken from the below expressions (36) and (37).

$$u \sim N(0, \phi_u^2), \quad v \sim N(0, \phi_v^2) \quad (36)$$

$$\phi_u = \left[\frac{\Gamma_1\,(1+\omega) \times sin\left(\pi \times \frac{\omega}{2}\right)}{\Gamma_1\,[(1+\omega)/2] \times \omega}\right], \quad \phi_v = 1 \quad (37)$$

The exploitation phase is enhanced by the updating points around the solutions in a spiral path. Using logarithmic spiral function, it is expressed as follows.

$$A^i_{s\_NW} = \left|A_{Best} - A^i_s\right| e^{bt}\cos(2\pi t) + A_{Best} \quad (38)$$

Here, $b$ denotes a constant to define the logarithmic spiral shape.

$$PAR(t) = PAR_{min} + \left(\frac{PAR_{max} - PAR_{min}}{T_{max}}\right) \times t \quad (39)$$

where, $PAR_{max}$ and $PAR_{min}$ are the maximum and the minimum $PAR$ limits.

It should be point out here that, to balance between the exploration and exploitation phases of the proposed algorithm an adaptive operator is utilized for this manner. This value is varied from $PAR_{min}$ to $PAR_{max}$ with the iterative process which are selected to be 0.4 and 0.85, respectively. The value of the $PAR$ is compared with $r$ which represents a generated random value within [0-1]. At the initial iterative process, the value of $PAR$ is small. Hence the probability of updating the search agents based on levy flight will be high. The opposite of that the probability of updating search agents based on the logarithmic spiral will be high at the final iterative process.

The methodology of application the modified LAPO for solving the ORPD with optimal integration of the TCSC and SVC is given as follows:

*Step 1:* Set the algorithm parameters including maximum number of iterations, search agent number.

*Step 2:* Define the system data including:
- Line data.
- Bus data.
- Generators data.
- The upper and lower boundaries of the control variables: $V_G$, $T_C$, $Q_C$, location TCSC, size TCSC, location SVC, size SVC.
- The upper and lower boundaries of the dependent variables: $V_L$, $Q_G$, $S_L$.

*Step 3:* Initialize the search agents or the initial spot points according to (25). Then, calculate the objective function for each search agent.

*Step 4:* Final the average point of the search agent's ant its objective function according to (34) and (35).

*Step 5:* Update the locations of agents according to (29) and (30).

*Step 6:* Compare between the new updated point and previous point and pick up the best solution based on (31).

*Step 7:* Update the value of the PAR according to (39)

*Step 8:* Updating the locations of search agents as follows:
If < rand
Update the location of the search agent based on Levy flight using (34)
Else
Update the location of the search agent based on the logarithmic spiral using (38)
End

*Step 9:* Calculate the objective function for the updated search agents. The accept the updated search agent if its value is better than the previous search agent.

*Step 10:* Repeat steps from 4 to 9 until the termination criteria is satisfied (The current iteration equals to the maximum number of iteration).

*Step 11:* Capture the optimal solution and its corresponding control variables.

## V. RESULTS AND DISCUSSION

In this section, the simulations are performed on MATLAB 2015 using Windows 10, Intel®Core$^{TM}$i7-8550U CPU @ 1.80 GHz with 8GB RAM. The MATPOWER package is used to ensures the detailed outcomes by running the load flow analysis. The sections A and B have been considered. The preformation of analysis is given as follows.

A. Considering with and without optimal allocation of FACTS Using IEEE 30-bus standard

**TABLE 1.** Parameters selection for modified MLAPO with and without allocation of FACTS using IEEE30 and 57-bus standards.

| Parameters | IEEE30 | IEEE57 |
|---|---|---|
| Population Size | 25 | 25 |
| Iterations | 50 | 50 |
| Independent Runs | 30 | 30 |

B. Considering with and without optimal allocation of the FACTS Using IEEE 57-bus standard

The concept of using FACTS is to secure the operation with minimizing the $P_{losses}$, $VD$ and $OC$.

The parameter values are taken from Table. 1 while performing the simulations using MLAPO and other optimization techniques, such as LAPO, PSO, ALO, EO, MPA, WOA and SCA, respectively. It should be highlighted here that these parameters are selected empirically where the importance of this act is having a compromise between optimal solution and run time or minimum number of iterations, which is a necessary feature of the optimization algorithms.

The values of the reactive power of generating units limits considered for the standard IEEE30 are between $Q_{max} = [200\ 100\ 80\ 60\ 50\ 60\ ]$, $Q_{min} = [-20\ -20\ -15\ -15\ -10\ -15]$. Whereas, for standard IEEE57, the reactive power of generating units limits are between $Q_{max} = [200\ 50\ 60\ 25\ 200\ 9\ 155]$, $Q_{min} = [-140\ -17\ -10\ -8\ -140\ -3\ -150]$, respectively. It is worst mentioning that the location of the TCSCs and SVCs are considered as a discrete control variable. The boundaries of TCSCs are selected to be "from 1 to 41" for IEEE30 while for IEEE57 "from 1 to 80" which represents the possible lines that TCSC can be incorporated in these lines. While, the boundaries of SVCs are from "1 to 30" for IEEE30 and from "1 to 57" for IEEE57 which represents the possible buses that SVC can be incorporated in these buses.

### A. CONSIDERING WITH AND WITHOUT OPTIMAL ALLOCAITON OF FACTS DEVICES USING IEEE 30-BUS STANDARD

The IEEE 30-bus standard consisting of six generators 1, 2, 5, 8, 11 and 13, four transformers tap settings at buses 6-9, 6-10, 4-12 and 28-27 while nine shunts compensators. The bus 1 is selected as the slack bus. The total demand of the active and the reactive powers are 283.4 MW and 126.2 MVAR, respectively. The base case is considered with optimal allocation of the FACTS devices with active *Plosses* 7.11 MW and $OC$ is reported to 3.73016($), respectively. While, in case of without optimal allocation of FACTS devices, the base case for active power loss is 5.811 MW [45] and for $VD$ is 0.8691 p.u. [21], respectively. In [2], the TCSCs are connected to the line 25, 41, 28 and 5 while SVCs are connected to the lines 22, 4, 28 and 20. The detection of the weak buses can be found through Voltage Collapse Proximity Indication Method (VCPI) method. It is worst mentioning that the TCSC cost is slightly more than the SVC

**TABLE 2.** Control variable limits for optimal allocation of FACTS devices using IEEE30-bus [2].

| Constraints | IEEE30 (FACTS Devices) |
|---|---|
| Transformer | 0.9 – 1.1 |
| TCSC | 0.0 – 0.08 |
| SVC | 0.0 – 0.20 |

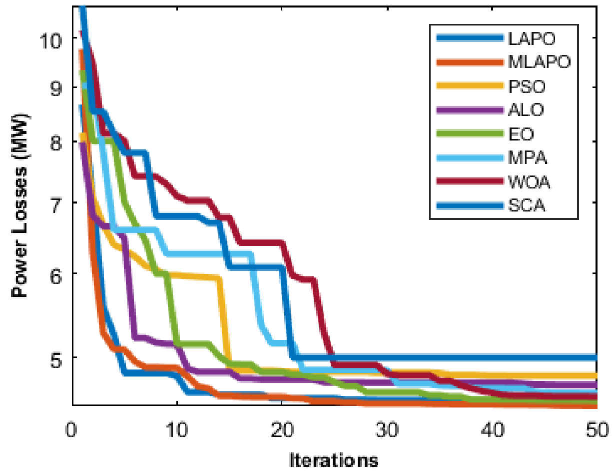


**FIGURE 5.** Minimization of power losses without optimal allocation of the FACTS devices using IEEE30 standard.

cost according to (16) and (17). The limits of the control variables with optimal allocation of the FACTS devices are given in Table. 2.

The section A is divided into five further sub-sections given as follows:

1. Minimization of Power Losses without optimal allocation of the FACTS Devices
2. Minimization of Voltage Deviation without optimal allocation of the FACTS Devices
3. Minimization of Power Losses with optimal allocation of the FACTS Devices
4. Minimization of Voltage Deviation with optimal allocation of the FACTS Devices
5. Minimization of Overall Operating Cost with optimal allocation of the FACTS Devices

The selection of the parameters and limits of the control variables are taken from Table. 1 and 2.

#### 1) MINIMIZATION OF POWER LOSSES WITHOUT OPTIMAL ALLOCATION OF THE FACTS DEVICES

In this section, the first objective is to minimize the *Plosses* without optimal allocations of the TCSC and SVC applied to IEEE 30-bus system. Fig. 5 demonstrated the best convergence response achieved by MLAPO with 4.5086 MW value while the worst response is reported by SCA with 5.0063 MW.

In view of the base case 5.811 MW, the reduction in *Plosses* from the considered optimization techniques given in Table. 3 is given as follows. LAPO is 22.17%, PSO is

**TABLE 3.** Simulation results for all given objective functions with & without considering TCSC and SVC using IEEE 30-bus standard.

| Power Losses Without Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 4.6899 | 4.5434 | 5.7338 | 4.8303 | 5.0133 | 4.9689 | 4.9019 | 5.5603 |
| Best | 4.5258 | 4.5086 | 4.8137 | 4.7183 | 4.5595 | 4.6374 | 4.6007 | 5.0063 |
| Worst | 5.6560 | 4.6859 | 7.0902 | 4.9084 | 6.0871 | 5.8527 | 5.4667 | 6.4349 |
| Voltage Deviation Without Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 0.2588 | 0.1714 | 1.1818 | 0.3462 | 0.2773 | 0.2491 | 0.2856 | 0.5988 |
| Best | 0.1026 | 0.0908 | 0.3693 | 0.1057 | 0.1242 | 0.1269 | 0.1622 | 0.3225 |
| Worst | 1.1549 | 1.0954 | 1.4792 | 1.1665 | 1.1507 | 0.4787 | 0.4879 | 1.5899 |
| Power Losses with Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 4.6974 | 4.5185 | 5.8440 | 4.8250 | 4.8578 | 4.8858 | 4.8896 | 5.4875 |
| Best | 4.5175 | 4.4838 | 4.7323 | 4.6821 | 4.5160 | 4.5896 | 4.5962 | 4.9453 |
| Worst | 5.9853 | 4.5839 | 7.1589 | 4.9149 | 5.6482 | 5.6081 | 5.5807 | 6.5840 |
| Voltage Deviation with Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 0.2137 | 0.1429 | 0.4574 | 0.1916 | 0.2245 | 0.2468 | 0.2466 | 0.5004 |
| Best | 0.1315 | 0.0889 | 0.2526 | 0.1029 | 0.1163 | 0.1203 | 0.1258 | 0.2972 |
| Worst | 0.3532 | 0.2385 | 0.7243 | 0.3095 | 0.3879 | 0.3669 | 0.4083 | 0.6851 |
| Overall Operating Cost ($) with Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | $2.4851\times10^6$ | $2.4021\times10^6$ | $2.8428\times10^6$ | $2.5430\times10^6$ | $2.4998\times10^6$ | $2.5858\times10^6$ | $2.6159\times10^6$ | $2.8000\times10^6$ |
| Best | $2.3819\times10^6$ | $2.3588\times10^6$ | $2.6387\times10^6$ | $2.5053\times10^6$ | $2.3853\times10^6$ | $2.4371\times10^6$ | $2.4379\times10^6$ | $2.5523\times10^6$ |
| Worst | $2.6631\times10^6$ | $2.5197\times10^6$ | $3.2308\times10^6$ | $2.5882\times10^6$ | $2.6538\times10^6$ | $2.7361\times10^6$ | $2.8426\times10^6$ | $2.9708\times10^6$ |

**TABLE 4.** Comparison of different Algorithm with MLAPO for minimizing power losses (MW) without TCSC and SVC using IEEE30 standard.

| Algorithm | $Ploss(MW)$ | Algorithm | $Ploss(MW)$ | Algorithm | $Ploss(MW)$ |
|---|---|---|---|---|---|
| GWO [39] | 4.5538 | PSO-cf [54] | 4.5258 | PSOGWO [49] | 5.09037 |
| PSO [50] | 4.6862 | FODPSO [48] | 4.606 | SBDE [46] | 4.590 |
| MPA [21] | 4.5335 | QOTLBO [55] | 4.5594 | PSO-EE [38] | 4.6448 |
| FA-APTFPSO-IV [53] | 4.8664 | PSOGSA [58] | 4.5309 | LISA Strategy-1 [47] | 4.512 |
| FODPSO-EE [38] | 4.5971 | MSFS [57] | 4.5143 | ALO [56] | 4.5804 |
| HPSO-TS [50] | 4.5213 | WOA [51] | 4.5943 | JA [52] | 4.625 |

**TABLE 5.** Comparison of different Algorithm with MLAPO for minimizing voltage deviation (P.U.) without TCSC and SVC using IEEE30 standard.

| Algorithm | $VD(p.u)$ | Algorithm | $VD(p.u)$ |
|---|---|---|---|
| SPSO-TVAC [54] | 0.1354 | PSO-EE [38] | 0.1177 |
| SWT-PSO [54] | 0.1614 | FOPSO-EE [38] | 0.1057 |
| SSO [64] | 0.19304 | FPSOGSA [59] | 0.1025 |
| ALO [65] | 0.1192 | GSA-CSS [66] | 0.12394 |

17.16%, ALO is 18.80%, EO is 21.54 %, MPA is 20.19%, WOA is 20.83%, SCA is 13.85% while MLAPO technique is 22.41%. In addition, to further validate the performance of MLAPO, the other well-known optimization techniques given in Table. 4 are added for comparison with the base case. GWO is 21.63%, PSO 19.36%, MPA is 21.98%, FA-APTFPSO-IV is 16.25%, FODPSO-EE is 20.89%, HPSO-TS is 22.19%, PSO-cf is 22.12%, FODPSO is 20.74%, QOTLBO is 21.54%, PSOGSA is 22.03%, MSFS is 22.31%, WOA is 20.94%, PSOGWO is 12.40%, SBDE is 21.01%, PSO-EE is 20.07%, LISA Strategy-I is 22.35%, ALO is 21.77% and JA is reported as 20.41%.

The best values of the control variables for this case are given in Table. 6, where the bounds are within their pre-

**TABLE 6. Output of control variables without TCSC and SVC for minimizing the power losses (MW) using IEEE30 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| VG 1 | 1.099754 | 1.099997 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| VG 2 | 1.093459 | 1.094806 | 1.054651 | 1.061633 | 1.072404 | 1.094695 | 1.083121 | 1.077702 |
| VG 5 | 1.074073 | 1.074461 | 1.1 | 1.086489 | 1.1 | 1.082554 | 1.099106 | 1.09115 |
| VG 8 | 1.077604 | 1.076556 | 1.1 | 1.072618 | 1.075486 | 1.080692 | 1.074424 | 1.1 |
| VG 11 | 1.096062 | 1.059337 | 1.1 | 1.062655 | 1.085107 | 1.090006 | 1.099984 | 1.077794 |
| VG 13 | 1.099656 | 1.083132 | 1.1 | 1.057084 | 1.1 | 1.062112 | 1.090823 | 1.1 |
| TC6-9 | 1.039664 | 1.029202 | 1.1 | 1.034351 | 0.952053 | 0.959276 | 0.992041 | 0.9 |
| TC 6-10 | 0.901712 | 0.902583 | 0.9 | 1.083263 | 1.090658 | 1.050471 | 0.901818 | 1.1 |
| TC 4-12 | 0.991217 | 0.98562 | 1.1 | 1.079649 | 0.966161 | 1.064576 | 1.029085 | 1.1 |
| TC 27-28 | 0.969735 | 0.967509 | 1.001896 | 1.051968 | 0.957664 | 0.989329 | 0.955182 | 1.006288 |
| QC 10 | 0.407723 | 0.613024 | 0 | 0.420497 | 2.921474 | 0.216917 | 0.617944 | 0 |
| QC 12 | 1.45003 | 1.886186 | 0 | 0.557942 | 0.03202 | 4.993796 | 3.852937 | 0 |
| QC 15 | 0.047734 | 0.059962 | 0.553569 | 1.023657 | 0.829296 | 0.011033 | 0.356295 | 0 |
| QC 17 | 0.133786 | 0.584036 | 0.257961 | 0.743088 | 0.708201 | 0.155109 | 0.048248 | 0 |
| QC 20 | 0.481895 | 0.546096 | 0 | 0.668573 | 0.02615 | 0.381862 | 0.003831 | 0 |
| QC 21 | 1.00096 | 1.398564 | 0.155932 | 0.420396 | 0.456094 | 2.065122 | 0.013555 | 0 |
| QC 23 | 0.025984 | 0.298386 | 0.615545 | 0.2451 | 0 | 0.373098 | 0.523767 | 0.198909 |
| QC 24 | 0.985862 | 0.651421 | 0 | 0.531265 | 0.757886 | 0.391612 | 0.348471 | 0 |
| QC 29 | 0.24916 | 0.210219 | 0 | 0.245878 | 0.091544 | 0.581011 | 0.158675 | 0 |

**TABLE 7. Output of control variables without TCSC and SVC for minimizing the voltage deviation (P.U) using IEEE30 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| VG 1 | 1.018318 | 1.023095 | 1.1 | 1.012452 | 1.022856 | 1.021812 | 1.033078 | 1.062306 |
| VG 2 | 0.982571 | 0.982337 | 1.072106 | 0.995454 | 1.035253 | 1.009511 | 0.991648 | 1.1 |
| VG 5 | 1.073706 | 1.067511 | 1.1 | 1.01014 | 0.986232 | 1.06287 | 1.033612 | 1.001957 |
| VG 8 | 0.987595 | 0.96097 | 0.98381 | 0.995806 | 0.947599 | 0.968215 | 0.924121 | 1.030207 |
| VG 11 | 1.028276 | 0.995625 | 1.017337 | 1.006616 | 1.0796 | 1.087349 | 0.990871 | 1.014813 |
| VG 13 | 0.942059 | 0.99358 | 1.1 | 1.009048 | 0.997678 | 0.950675 | 0.995689 | 0.978279 |
| TC6-9 | 1.016323 | 1.004373 | 1.1 | 0.999409 | 1.090828 | 1.1 | 0.976461 | 1.099983 |
| TC 6-10 | 1.047863 | 1.027561 | 0.9 | 1.025751 | 0.954358 | 0.962586 | 1.099851 | 0.905925 |
| TC 4-12 | 0.97352 | 1.002978 | 1.1 | 1.00659 | 1.021424 | 0.990294 | 1.028927 | 0.9 |
| TC 27-28 | 0.983035 | 1.029185 | 0.963476 | 0.990379 | 1.010607 | 0.972795 | 0.991941 | 0.975962 |
| QC 10 | 1.067109 | 0.074451 | 0 | 1.538143 | 0.183929 | 0.457503 | 0.889796 | 2.006653 |
| QC 12 | 0.259296 | 0.594267 | 0 | 0.171841 | 0 | 1.900223 | 1.40038 | 0 |
| QC 15 | 1.072435 | 1.137288 | 1.279319 | 0.909056 | 0.926611 | 0.002043 | 0.771066 | 0 |
| QC 17 | 0.952 | 0.804457 | 0 | 0.566333 | 0.471408 | 0.461974 | 2.83841 | 0 |
| QC 20 | 1.028252 | 1.21622 | 0.469405 | 0.509884 | 1.024091 | 0.39552 | 0.989431 | 0.001226 |
| QC 21 | 0.076411 | 1.192819 | 0.70912 | 1.002083 | 0.000438 | 0.937704 | 0.657981 | 0 |
| QC 23 | 0.129963 | 0.139191 | 0 | 0.393385 | 1.368732 | 0.002409 | 0.519379 | 0 |
| QC 24 | 1.322003 | 1.474671 | 0 | 1.214347 | 1.693139 | 1.251737 | 0.846001 | 0 |
| QC 29 | 0.374619 | 1.423308 | 0 | 0.446385 | 0.633373 | 0.195486 | 1.070687 | 0 |

defined limits. Fig. 5, Tables 3 and 4 demonstrated the best response achieved by MLAPO for this case.

### 2) MINIMIZATION OF VOLTAGE DEVIATION WITHOUT OPTIMAL ALLOCATION OF THE FACTS DEVICES

The 2$^{nd}$ objective is to minimize the *VD* without optimal allocation of the FACTS devices using IEEE 30-bus standard. In Table. 3, the simulation outcomes can be seen in case of minimizing the *VD* yielded by MLAPO, along the comparison with other considered optimization techniques, such as LAPO, PSO, ALO, EO, MPA, WOA and SCA, respectively. Fig. 6 demonstrated the best convergence performance achieved by MLAPO with 0.0908 p.u. while the worst case reported by PSO is 0.3693 p.u.

**TABLE 8. Output of control variables with TCSC and SVC for minimizing the power losses (MW) using IEEE30 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| VG 1 | 1.1 | 1.099942 | 1.1 | 1.1 | 1.099131 | 1.099927 | 1.1 | 1.1 |
| VG 2 | 1.093191 | 1.093762 | 1.1 | 1.075013 | 1.072511 | 1.075785 | 1.073649 | 1.1 |
| VG 5 | 1.07353 | 1.07479 | 1.067261 | 1.080792 | 1.095389 | 1.098589 | 1.099783 | 1.1 |
| VG 8 | 1.073895 | 1.077093 | 1.024259 | 1.083525 | 1.073547 | 1.077985 | 1.076182 | 1.1 |
| VG 11 | 1.082431 | 1.092712 | 1.1 | 1.065035 | 1.099875 | 1.099004 | 1.099764 | 1.1 |
| VG 13 | 1.028801 | 1.039664 | 1.1 | 1.083753 | 1.098348 | 1.099507 | 1.09859 | 1.014362 |
| TC6-9 | 0.974158 | 1.032659 | 1.1 | 1.038788 | 1.018377 | 1.070787 | 1.099825 | 0.9 |
| TC 6-10 | 1.049196 | 0.900803 | 0.9 | 1.040863 | 0.90035 | 0.914541 | 0.903834 | 1.1 |
| TC 4-12 | 1.005208 | 0.959303 | 0.980087 | 1.050863 | 0.984476 | 0.979288 | 0.965928 | 0.938552 |
| TC 27-28 | 0.979386 | 0.963484 | 0.979603 | 1.041078 | 0.968717 | 0.958105 | 0.966809 | 0.955825 |
| QC 10 | 1.211848 | 0.078506 | 0 | 0.587748 | 0.087587 | 0.307171 | 0.117988 | 0 |
| QC 12 | 3.121308 | 0.545825 | 0 | 0.611491 | 1.023368 | 0.716361 | 0.183261 | 0.055644 |
| QC 15 | 0.352978 | 0.272355 | 0 | 0.514748 | 0.002002 | 0.141099 | 0.257374 | 0.019192 |
| QC 17 | 0.817861 | 0.552981 | 0 | 0.545868 | 0.011739 | 0.418976 | 0.385462 | 0 |
| QC 20 | 0.388748 | 0.308703 | 0 | 0.515942 | 0.628676 | 0.249045 | 0.323787 | 0 |
| QC 21 | 0.362779 | 1.016975 | 0 | 0.618307 | 0.357749 | 0.044312 | 2.376335 | 0.935344 |
| QC 23 | 0.002682 | 0.365421 | 0 | 0.532459 | 0.095985 | 0.712177 | 0.393714 | 0 |
| QC 24 | 1.066531 | 0.594197 | 0 | 0.522169 | 0.925788 | 0.149374 | 0.069021 | 0 |
| QC 29 | 0.143146 | 0.002672 | 0 | 0.505966 | 0.298383 | 0.004032 | 0.103277 | 0 |

**TABLE 9. Output Of control variables with TCSC and SVC for minimizing the voltage deviation (P.U.) using IEEE30 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| VG 1 | 1.029883 | 1.029357 | 1.011991 | 1.008161 | 1.010424 | 1.012225 | 1.01476 | 1.034658 |
| VG 2 | 1.02759 | 1.065465 | 0.9 | 1.000415 | 0.997252 | 0.99599 | 1.060695 | 1.030743 |
| VG 5 | 0.982765 | 1.021365 | 1.022275 | 1.006595 | 0.968824 | 1.062305 | 0.98116 | 1.062521 |
| VG 8 | 0.967014 | 0.957123 | 0.986412 | 1.004665 | 1.017831 | 0.967871 | 0.948988 | 1.016648 |
| VG 11 | 0.996576 | 0.983292 | 1.06597 | 0.984863 | 0.987576 | 1.005941 | 1.047273 | 1.072532 |
| VG 13 | 0.980398 | 0.946093 | 1.008017 | 0.994286 | 1.006759 | 0.932787 | 0.940125 | 0.994113 |
| TC6-9 | 1.058675 | 0.988896 | 1.088685 | 0.989892 | 1.022275 | 1.041117 | 1.099978 | 0.9 |
| TC 6-10 | 1.012604 | 1.097998 | 1.1 | 0.998657 | 0.928032 | 1.006536 | 1.038463 | 1.089741 |
| TC 4-12 | 0.990654 | 0.948775 | 1.1 | 1.007583 | 1.006264 | 0.986339 | 0.967448 | 0.944581 |
| TC 27-28 | 0.965209 | 0.986723 | 0.942462 | 0.988376 | 0.992297 | 0.987156 | 0.988215 | 0.946391 |
| QC 10 | 0.567076 | 0.499573 | 5 | 0.449389 | 0 | 1.228458 | 1.171372 | 0 |
| QC 12 | 0.549661 | 0.377689 | 3.117844 | 0.41465 | 1.176325 | 1.091913 | 1.693944 | 0 |
| QC 15 | 0.497465 | 0.208723 | 2.591753 | 1.775692 | 0.161141 | 0.736428 | 0.071359 | 0 |
| QC 17 | 1.502801 | 0.381827 | 0 | 0.425046 | 0.041588 | 1.360886 | 0.008314 | 0 |
| QC 20 | 1.362405 | 0.773225 | 0 | 0.373883 | 1.412389 | 0.789133 | 1.140478 | 0 |
| QC 21 | 0.344956 | 0.987365 | 0 | 1.621652 | 1.071114 | 0.154855 | 1.676208 | 0 |
| QC 23 | 0.297904 | 0.206032 | 0 | 0.327088 | 0.772914 | 0.530845 | 1.73006 | 0 |
| QC 24 | 0.994358 | 1.152097 | 0.099239 | 0.399191 | 0.915143 | 0.5045 | 0.940716 | 0 |
| QC 29 | 0.361326 | 0.468594 | 0 | 0.699546 | 0.532904 | 0.83843 | 0.69011 | 0.641027 |

In view of the base case 0.8691 p.u., the reduction in *VD* of the simulation outcomes given in Table. 3 is as follows. LAPO is 88.19%, PSO is 57.51%, ALO is 87.84%, EO is 85.71%, MPA is 85.40%, WOA is 81.34%, SCA is 62.89% while MLAPO is reported to 89.55%.

To legalize performance of the MLAPO, the simulation results given in Table. 5 are further compared with the base case. SPSO-TVAC is 84.4 %, SWT-PSO is 81.43%, SSO is 77.79%, ALO is 86.28%, PSO-EE is 86.46%, FOPSO-EE is 87.84%, FPSOGSA is 88.21% and GSA-CSS is 85.74%.

**TABLE 10. Output Of control variables with TCSC and SVC for minimizing the operating cost ($) using IEEE30 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| VG 1 | 1.1 | 1.1 | 1.1 | 1.099884 | 1.096581 | 1.1 | 1.1 | 1.1 |
| VG 2 | 1.095912 | 1.093598 | 1.043957 | 1.094385 | 1.088991 | 1.075745 | 1.094664 | 1.061287 |
| VG 5 | 1.075563 | 1.074491 | 1.1 | 1.069851 | 1.094686 | 1.096568 | 1.075597 | 1.1 |
| VG 8 | 1.07734 | 1.076024 | 1.1 | 1.080508 | 1.071946 | 1.078327 | 1.077425 | 1.1 |
| VG 11 | 1.099143 | 1.079835 | 1.1 | 1.077788 | 1.090111 | 1.082847 | 1.098463 | 1.1 |
| VG 13 | 1.024114 | 1.079117 | 1.1 | 1.075876 | 1.035874 | 1.032689 | 1.026391 | 1.1 |
| TC6-9 | 0.946911 | 0.992286 | 1.1 | 1.071929 | 0.97279 | 1.073514 | 1.006524 | 0.908564 |
| TC 6-10 | 1.1 | 0.930022 | 0.901031 | 1.072075 | 0.963572 | 0.929235 | 1.084633 | 1.1 |
| TC 4-12 | 1.011705 | 0.957474 | 0.986058 | 1.074981 | 0.953726 | 0.981292 | 0.968695 | 0.939919 |
| TC 27-28 | 0.966799 | 0.97195 | 0.972877 | 1.059371 | 0.974957 | 0.984834 | 0.991387 | 1.01215 |
| QC 10 | 0.094154 | 0.049132 | 0 | 0.732617 | 0.151679 | 0.738908 | 0.002604 | 0.015721 |
| QC 12 | 2.700768 | 0.62725 | 0.035626 | 0.330645 | 0.764152 | 1.218984 | 0.236547 | 0 |
| QC 15 | 0.50461 | 0.414577 | 0 | 0.546224 | 0.453893 | 0.945308 | 0.746846 | 0.005486 |
| QC 17 | 0.484008 | 0.317142 | 0.046761 | 0.571486 | 0.423969 | 0.038815 | 0.977546 | 0 |
| QC 20 | 0.400632 | 0.311071 | 0 | 0.410741 | 0.302937 | 0.671135 | 0.018004 | 0 |
| QC 21 | 1.050884 | 1.220371 | 0 | 0.419384 | 0.038735 | 0.072045 | 0.299545 | 0 |
| QC 23 | 0.246947 | 0.127171 | 0 | 0.339135 | 0.159757 | 0 | 0.00135 | 0 |
| QC 24 | 0.235434 | 0.745484 | 0 | 0.502544 | 0.810769 | 0.831455 | 1.673301 | 0 |
| QC 29 | 0.043877 | 0.210311 | 0 | 0.421621 | 0.238182 | 0.454433 | 0.113986 | 0 |

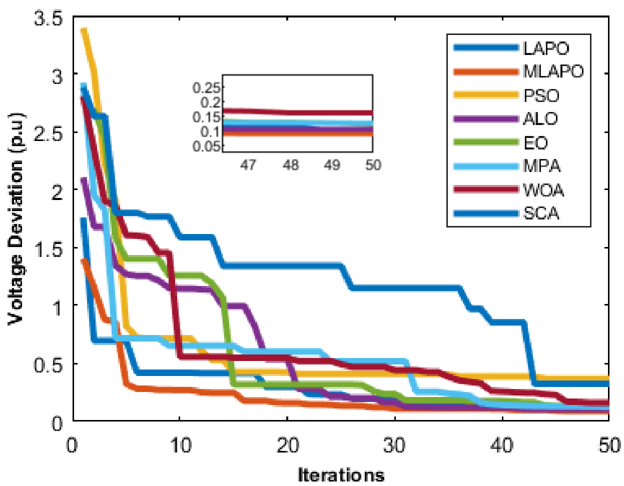


**FIGURE 6. Minimization of voltage deviation without optimal allocation of the FACTS devices using IEEE30 standard.**

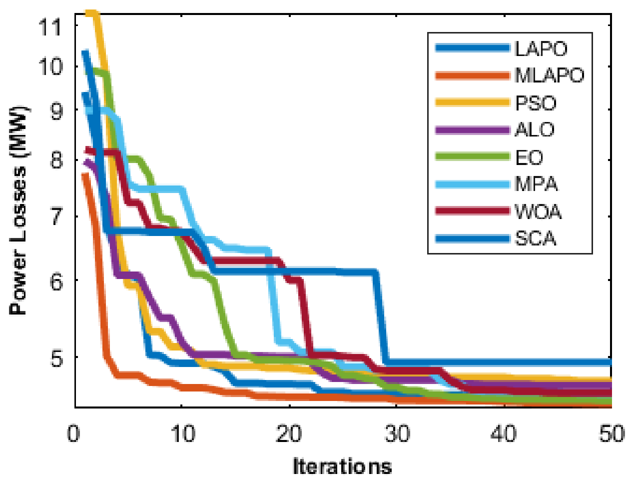


**FIGURE 7. Minimization power losses with optimal allocation of the FACTS devices using IEEE30 standard.**

The best values of the control variables for this case against the minimum value of *VD* are reported in Table. 7. Hence, the performance of MLAPO is superior to the reported algorithms.

### 3) MINIMIZATION OF POWER LOSSES WITH OPTIMAL ALLOCATION OF THE FACTS DEVICES

In this case, the 3$^{rd}$ objective is to minimize the *Plosses* with optimal allocations of the FACTS devices using IEEE 30-bus standard. The simulation outcomes of the considered different techniques including MLAPO are reported in Table. 3 with the best, worst and average values. Fig. 7 demonstrated the best convergence response achieved by MLAPO with 4.4838 MW, while the worst case reported by SCA is 4.9453 MW.

Considering the base case 7.11 MW, the reduction in *Plosses* of the different optimization techniques given in Table. 3 are reported as follows. LAPO is 36.4627 %, PSO is 33.4416 %, ALO is 34.1477 %, EO is 36.4838 %, MPA is 35.4487 %, WOA is 35.2558 %, SCA is 30.4458 % while MLAPO is reported as 36.9367 %. While compared to the

**TABLE 11.** Optimal allocations and sizes of TCSC and SVC for different considered objective functions using IEEE30 bus standard.

| | | Parameters | TCSC1 | TCSC2 | TCSC3 | TCSC4 | SVC1 | SVC2 | SVC3 | SVC4 |
|---|---|---|---|---|---|---|---|---|---|---|
| LAPO | Plosses | Size (p.u) | 0.071965 | 0.005328 | 0.03257 | 0.032562 | 0.02919 | 0.015679 | 0 | 0.071965 |
| | | Location | 11 | 39 | 6 | 38 | 6 | 28 | 16 | 7 |
| | VD | Size (p.u) | 0.038069 | 0.06939 | 0.047574 | 0.024565 | 0.07218 | 0.027891 | 0.07331 | 0.00984 |
| | | Location | 30 | 20 | 4 | 30 | 28 | 3 | 16 | 13 |
| | *OC* | Size (p.u) | 0.000255 | 0.010755 | 0.00148 | 0.044186 | 0.04564 | 0.000809 | 0.04629 | 0.007282 |
| | | Location | 8 | 31 | 2 | 20 | 2 | 2 | 4 | 1 |
| MLAPO | Plosess | Size (p.u) | 0.044178 | 0.026178 | 0 | 0.039022 | 0.00528 | 0.135575 | 0.00430 | 0.044178 |
| | | Location | 21 | 28 | 36 | 30 | 13 | 3 | 14 | 5 |
| | VD | Size (p.u) | 0.069368 | 0.003187 | 0.02845 | 0.068203 | 0.11216 | 0.002854 | 0.12462 | 0.060961 |
| | | Location | 33 | 35 | 27 | 9 | 4 | 3 | 12 | 6 |
| | *OC* | Size (p.u) | 0.007811 | 0.002056 | 0.030512 | 0.045897 | 0.01573 | 0.193072 | 0.2 | 0.00143 |
| | | Location | 30 | 7 | 33 | 19 | 2 | 19 | 5 | 29 |
| PSO | Plosses | Size (p.u) | 0 | 0.08 | 0.08 | 0.08 | 0.05472 | 0.2 | 0.2 | 0 |
| | | Location | 21 | 14 | 19 | 25 | 20 | 15 | 5 | 24 |
| | VD | Size (p.u) | 0 | 0.08 | 0 | 0.08 | 0.02144 | 0.2 | 0.2 | 0 |
| | | Location | 26 | 1 | 24 | 28 | 10 | 5 | 30 | 18 |
| | *OC* | Size (p.u) | 0.08 | 0.08 | 0.08 | 0.08 | 0.2 | 0 | 0.02 | 0.2 |
| | | Location | 38 | 39 | 16 | 41 | 18 | 19 | 14 | 13 |
| ALO | Plosses | Size (p.u) | 0.505966 | 0.007952 | 0.008782 | 0.008488 | 0.00920 | 0.021035 | 0.02400 | 0.022819 |
| | | Location | 6 | 6 | 6 | 6 | 5 | 4 | 4 | 5 |
| | VD | Size (p.u) | 0.007835 | 0.026825 | 0.022847 | 0.024111 | 0.02026 | 0.033409 | 0.04833 | 0.024974 |
| | | Location | 10 | 4 | 5 | 13 | 4 | 12 | 11 | 4 |
| | *OC* | Size (p.u) | 0.014151 | 0.011496 | 0.010546 | 0.00585 | 0.01776 | 0.023373 | 0.01704 | 0.018648 |
| | | Location | 4 | 5 | 4 | 5 | 4 | 3 | 3 | 4 |
| EO | Plosses | Size (p.u) | 0.298383 | 0.00186 | 0.033277 | 0.012137 | 0.04016 | 0.053457 | 0.05925 | 0.007722 |
| | | Location | 11 | 5 | 40 | 35 | 6 | 26 | 1 | 21 |
| | VD | Size (p.u) | 0.046565 | 0.013547 | 0.00848 | 0.033996 | 0.00023 | 0.004406 | 0.00146 | 0.004052 |
| | | Location | 40 | 33 | 10 | 1 | 18 | 28 | 1 | 5 |
| | *OC* | Size (p.u) | 0.056763 | 0.001105 | 0.008149 | 0.040469 | 0.07170 | 0.087594 | 0.01697 | 0.018541 |
| | | Location | 37 | 5 | 40 | 8 | 15 | 8 | 8 | 13 |
| MPA | Plosses | Size (p.u) | 0.00186 | 0.033277 | 0.012137 | 0.040162 | 0.05346 | 0.059247 | 0.00772 | 0.002866 |
| | | Location | 8 | 41 | 27 | 33 | 11 | 12 | 17 | 28 |
| | VD | Size (p.u) | 0.030041 | 0.023139 | 0.045572 | 0.057306 | 0.03111 | 0.085411 | 0.03822 | 0.086562 |
| | | Location | 5 | 15 | 26 | 13 | 23 | 4 | 13 | 8 |
| | *OC* | Size (p.u) | 0.031157 | 0.079809 | 0.08 | 0.079959 | 0.09489 | 0.129537 | 0.04639 | 0.016917 |
| | | Location | 18 | 26 | 1 | 5 | 19 | 8 | 29 | 27 |
| WOA | Plosses | Size (p.u) | 0.103277 | 0.01805 | 0.027542 | 0.0462 | 0.02115 | 0.021869 | 0.03335 | 0.068844 |
| | | Location | 25 | 32 | 26 | 12 | 16 | 1 | 8 | 8 |
| | VD | Size (p.u) | 0.01659 | 0.04602 | 0.012481 | 0.004879 | 0.01257 | 0.051695 | 0.08398 | 0.061499 |
| | | Location | 5 | 14 | 21 | 27 | 21 | 7 | 10 | 11 |
| | *OC* | Size (p.u) | 0.08 | 0.005894 | 0.052923 | 0.026392 | 0.11037 | 0.02428 | 0.0599 | 0.056316 |
| | | Location | 6 | 1 | 1 | 1 | 15 | 1 | 9 | 1 |
| SCA | Plosses | Size (p.u) | 0.076009 | 0.046638 | 0 | 0 | 0.00012 | 0 | 0.2 | 0 |
| | | Location | 12 | 1 | 1 | 15 | 4 | 4 | 12 | 2 |
| | VD | Size (p.u) | 0 | 0 | 0.013089 | 0.000156 | 0.00684 | 0 | 0.00017 | 0.019233 |
| | | Location | 1 | 5 | 26 | 2 | 6 | 13 | 9 | 2 |
| | *OC* | Size (p.u) | 0 | 0.012628 | 0.0229 | 0 | 0.13088 | 0.164603 | 0.08761 | 0.08741 |
| | | Location | 14 | 1 | 19 | 20 | 20 | 30 | 3 | 2 |

based case 5.811 MW of without considering FACTS devices, the result computed by MLAPO for this case is reported 22.84 % less than the base case. In addition, to further authenticate performance of MLAPO, the outcomes of other well-known optimization techniques are compared to the base case. PSO-EE [38] is 27.3207 %, FOPSO-EE [38] is 27.3235 %, QODE [2] is 25.7384 %, WOA [2] is 10.9282%, QOGWO [2] is 10.9564 %, SPSO [69] is 26.8917 % and BBO [32] is 37.0141 %. The optimal sizes and placements of TCSCs and SVCs are given in Table. 11. While, the control variables are provided in VIII. The overall simulation results demonstrated the best performance achieved by the MLAPO to reduce the *Plosses* using FACTS.

**TABLE 12.** Control variable limits for optimal allocation of TCSC and SVC using IEEE57 bus standard [2].

| Constraints | IEEE57 (TCSC, SVC) |
|---|---|
| Transformer | 0.9 – 1.1 |
| TCSC | 0.0 – 0.11 |
| SVC | 0.0 – 0.20 |

### 4) MINIMIZATION OF VOLTAGE DEVIATION WITH OPTIMAL ALLOCATION OF THE FACTS DEVICES

The 4$^{th}$ objective is to minimize *VD* with optimal allocation TCSCs and SVCs. Fig. 8 illustrated the best performance achieve by MLAPO with 0.0889 p.u., and the worst performance achieved by SCA with 0.2972 p.u.

**TABLE 13.** Simulation results for all given objective functions with & without optimal allocation of TCSC and SVC using IEEE 57-BUS standard.

| Power Losses Without Optimal Allocation of the FACTS Devices (TCSC and SVC) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 23.7637 | 22.9068 | 24.5572 | 25.2969 | 23.4277 | 23.7427 | 23.7606 | 28.5176 |
| Best | 22.8879 | 22.6081 | 23.3163 | 24.2269 | 22.7733 | 23.0773 | 23.1421 | 26.0042 |
| Worst | 24.6038 | 23.3596 | 25.6354 | 26.4758 | 25.0239 | 24.5394 | 24.6902 | 30.9019 |
| Voltage Deviation Without Optimal Allocations of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 0.8351 | 0.7129 | 1.4766 | 1.0522 | 0.9488 | 0.9063 | 0.8796 | 2.0495 |
| Best | 0.6893 | 0.6111 | 1.1737 | 0.7560 | 0.7778 | 0.6927 | 0.7176 | 1.1187 |
| Worst | 1.0146 | 0.9327 | 1.8522 | 1.4450 | 1.2971 | 1.1085 | 1.1782 | 2.8712 |
| Power Losses with Optimal Allocations of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 23.3498 | 22.2205 | 24.3889 | 24.4336 | 22.1544 | 22.8089 | 22.7118 | 26.8366 |
| Best | 22.6187 | 21.4448 | 22.7316 | 23.7834 | 21.6485 | 21.6627 | 21.8349 | 25.0183 |
| Worst | 23.8487 | 22.8117 | 24.8573 | 25.6613 | 22.8090 | 24.0604 | 23.7435 | 28.6377 |
| Voltage Deviation with Optimal Allocations of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | 0.6593 | 0.5278 | 1.1877 | 0.8416 | 0.8201 | 0.6997 | 0.7226 | 1.6296 |
| Best | 0.5147 | 0.4383 | 0.9580 | 0.6302 | 0.6472 | 0.5293 | 0.4829 | 1.1906 |
| Worst | 0.8152 | 0.6079 | 1.4454 | 1.1148 | 1.0975 | 0.8412 | 0.9123 | 1.9955 |
| Overall Operating Cost with Optimal Allocations of the FACTS Devices (TCSC and SVC) | | | | | | | | |
| | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
| Average | $1.2086\times10^7$ | $1.1415\times10^7$ | $1.2674\times10^7$ | $1.2797\times10^7$ | $1.1473\times10^7$ | $1.1837\times10^7$ | $1.1709\times10^7$ | $1.3917\times10^7$ |
| Best | $1.1394\times10^7$ | $1.1165\times10^7$ | $1.1616\times10^7$ | $1.2456\times10^7$ | $1.1199\times10^7$ | $1.1415\times10^7$ | $1.1397\times10^7$ | $1.2768\times10^7$ |
| Worst | $1.2491\times10^7$ | $1.1990\times10^7$ | $1.3140\times10^7$ | $1.3189\times10^7$ | $1.1787\times10^7$ | $1.2365\times10^7$ | $1.2266\times10^7$ | $1.5064\times10^7$ |

**TABLE 14.** Comparison of different Algorithm with MLAPO for minimize power losses (MW) without TCSC and SVC using IEEE57 standard.

| Algorithm | $Ploss(MW)$ | Algorithm | $Ploss(MW)$ | Algorithm | $Ploss(MW)$ |
|---|---|---|---|---|---|
| ALO [56] | 24.1025 | MPSO [60] | 23.51 | FODPSO [48] | 26.680 |
| AGA [60] | 24.56 | PSO-EE [38] | 26.4614 | PSO [61] | 27.842 |
| ICA [61] | 27.125 | PFA [63] | 24.6752 | FA-APTFPSO-IV [53] | 24.0878 |
| FPSOGSA [59] | 22.9185 | CBA-III [62] | 22.0162 | CGA [60] | 25.24 |
| CBA-IV [62] | 21.9627 | ICA-PSO [61] | 27.195 | FOPSO-EE [38] | 26.4390 |

**TABLE 15.** Comparison of different Algorithm MLAPO for minimizing the voltage deviation (P.U.) without TCSC and SVC using IEEE 57-bus.

| Algorithm | $VD(p.u)$ | Algorithm | $VD(p.u)$ |
|---|---|---|---|
| CLPSO [67] | 1.0929 | SGA (Ff1) [68] | 2.7021 |
| ICA [61] | 0.7952 | PSO [61] | 0.8007 |
| ICA-PSO [61] | 0.7130 | FODPSO [48] | 0.7102 |
| FPSOGSA [59] | 0.8017 | | |

The simulation outcomes for *VD* are given in Table. 3 where their best, worst and the average values are shown. Judging from Table. 3, the result computed from MLAPO is less than the other given techniques, such as LAPO is 32.3954 %, PSO is 64.8060 %, ALO is 13.6054 %, EO is 23.5597 %, MPA is 26.1014 %, WOA is 29.3322 % and SCA is 70.0875 %, respectively. The optimal sizes and placements of TCSCs and SVCs are given in Table. 11. While, the control

**TABLE 16. Output of control variables without TCSC and SVC for minimizing the power losses (MW) using IEEE57 bus standard.**

| Control Variables | LAPO | MLAPO (proposed) | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| V (1) | 1.098727 | 1.1 | 1.1 | 1.1 | 1.097526 | 1.099978 | 1.1 | 1.093433 |
| V (2) | 1.09008 | 1.092321 | 1.1 | 1.09612 | 1.084969 | 1.099917 | 1.099979 | 1.1 |
| V (3) | 1.097858 | 1.1 | 1.1 | 1.080123 | 1.095921 | 1.099914 | 1.096353 | 1.1 |
| V (6) | 1.085874 | 1.08327 | 1.1 | 1.081603 | 1.1 | 1.07023 | 1.092539 | 1.052611 |
| V (8) | 1.09606 | 1.095923 | 1.1 | 1.099128 | 1.093675 | 1.099943 | 1.098081 | 1.071411 |
| V (9) | 1.041692 | 1.096145 | 1.1 | 1.084822 | 1.018278 | 1.092512 | 1.099536 | 1.052223 |
| V (12) | 1.087307 | 1.094249 | 1.1 | 1.08543 | 1.088331 | 1.077856 | 1.071378 | 1.081967 |
| T 19 | 0.973081 | 1.044269 | 1.09836 | 1.095509 | 0.935354 | 1.087676 | 1.016825 | 0.976651 |
| T 20 | 1.05649 | 1.1 | 1.1 | 1.07488 | 1.068407 | 1.099991 | 1.048012 | 1.042465 |
| T 31 | 1.034003 | 1.098682 | 1.1 | 1.035115 | 1.077499 | 1.079064 | 1.0133 | 1.090828 |
| T 35 | 1.074095 | 1.043244 | 1.1 | 1.031959 | 1.041922 | 1.093816 | 1.03913 | 0.981895 |
| T 41 | 1.060278 | 1.094489 | 1.087624 | 1.056039 | 1.006346 | 1.099755 | 1.031254 | 0.990537 |
| T 46 | 0.995514 | 0.9 | 1.034611 | 1.064119 | 0.943961 | 0.954761 | 1.020402 | 0.9 |
| T 54 | 1.000761 | 1.067302 | 1.1 | 1.073581 | 0.942542 | 1.097026 | 0.996313 | 0.9 |
| T 58 | 0.985665 | 1.084294 | 0.990858 | 1.084993 | 0.983731 | 1.00043 | 1.014646 | 1.032934 |
| T 59 | 0.989374 | 1.076548 | 0.971677 | 1.036316 | 0.973292 | 0.98994 | 1.00172 | 1.064601 |
| T 65 | 0.993599 | 1.086383 | 0.981894 | 1.084826 | 0.965168 | 1.039982 | 0.969378 | 0.9 |
| T 66 | 0.949305 | 1.084249 | 0.955657 | 1.050652 | 0.937752 | 0.974608 | 0.96458 | 0.989273 |
| T 71 | 1.090613 | 1.093725 | 1.1 | 1.05082 | 1.067326 | 1.068748 | 0.955077 | 0.9 |
| T 73 | 1.039019 | 0.946017 | 1.1 | 1.1 | 1.077805 | 1.09666 | 1.027598 | 1.013924 |
| T 76 | 0.979018 | 1.063412 | 1.1 | 1.038817 | 1.051367 | 1.00292 | 1.003614 | 0.919906 |
| T 80 | 1.056145 | 1.097205 | 1.1 | 1.0715 | 1.034993 | 1.094936 | 1.067284 | 1.033848 |
| Q 3 | 2.766099 | 2.393915 | 2.524714 | 2.534692 | 2.207958 | 2.422158 | 1.605977 | 3.071105 |
| Q 25 | 1.124055 | 1.816252 | 0.041649 | 2.307374 | 0.886132 | 1.865936 | 1.941742 | 1.005576 |
| Q 53 | 1.148349 | 1.576742 | 1.64179 | 1.812619 | 1.332833 | 1.501376 | 2.114949 | 1.480476 |

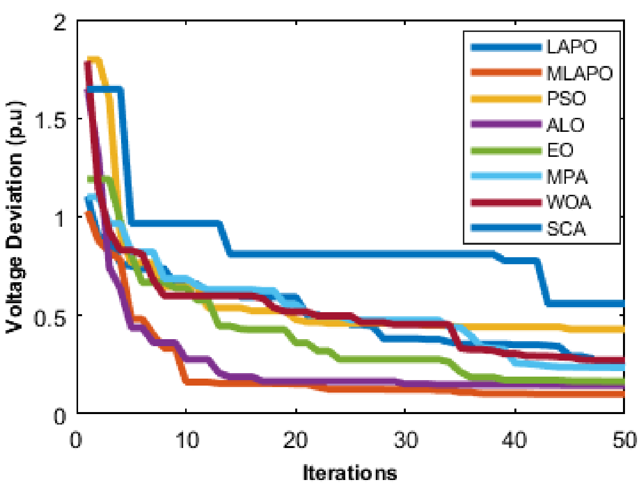


**FIGURE 8. Minimization voltage deviation with optimal allocation of the FACTS devices using IEEE30 standard.**

variables are provided in IX. Fig. 8, Table. 3 endorsed the efficient response getting from MLAPO using FACTS.

### 5) MINIMIZATION OF OVERALL OPERATING COST WITH OPTIMAL ALLOCATION OF THE FACTS

The 5th objective is to minimize the *OC* with optimal allocations of the SVC and TCSC using IEEE 30-bus system.

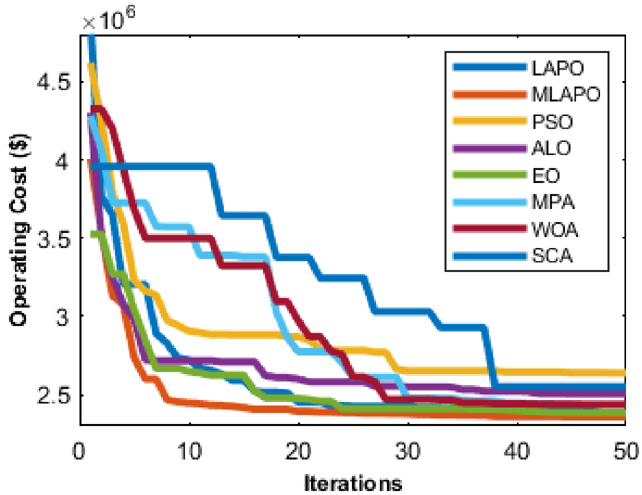


**FIGURE 9. Minimization of operating cost with optimal allocation of the FACTS devices using IEEE30 standard.**

The simulation results of different optimization techniques including MLAPO are reported with the average, best and worst values. Fig. 9 demonstrated the best convergence value achieved by MLAPO with the minimum cost reported to $2.3588 \times 10^6$ ($), while the worst response was computed by PSO with cost value $2.6387 \times 10^6$($).

**TABLE 17. Output of control variables without usiNG TCSC and SVC for minimizing the voltage deviation (P.u) using IEEE57 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| V (1) | 1.035075 | 1.004383 | 1.026945 | 1.032518 | 0.996577 | 1.005654 | 1.047022 | 0.956783 |
| V (2) | 1.047183 | 0.991582 | 1.036196 | 1.02525 | 1.001759 | 0.985804 | 1.079211 | 0.908697 |
| V (3) | 1.047068 | 1.028211 | 0.990664 | 1.030463 | 1.005395 | 1.041441 | 1.047372 | 1.024736 |
| V (6) | 0.997353 | 1.003276 | 1.03012 | 1.010479 | 1.00853 | 1.000213 | 1.020785 | 1.02454 |
| V (8) | 0.992557 | 1.044105 | 1.034406 | 0.998435 | 1.044675 | 0.997843 | 0.999207 | 1.036557 |
| V (9) | 0.997709 | 1.053374 | 1.06625 | 0.946738 | 1.013683 | 1.023943 | 1.018829 | 0.978512 |
| V (12) | 1.047947 | 1.029683 | 1.013035 | 1.019217 | 1.03893 | 1.015483 | 0.989553 | 1.053889 |
| T 19 | 0.983418 | 1.018947 | 0.9 | 0.934193 | 0.970956 | 0.97934 | 0.931554 | 0.951594 |
| T 20 | 0.99344 | 0.971121 | 1.1 | 1.024129 | 0.991882 | 0.975301 | 1.027061 | 0.994316 |
| T 31 | 1.000895 | 1.023065 | 0.982815 | 0.989165 | 0.981073 | 0.984672 | 0.993385 | 1.054558 |
| T 35 | 1.00757 | 0.97607 | 1.015715 | 0.997508 | 1.080853 | 1.00908 | 0.982901 | 1.030797 |
| T 41 | 0.979187 | 1.062152 | 0.999046 | 1.007971 | 1.010999 | 1.008434 | 1.012827 | 0.98067 |
| T 46 | 0.976442 | 0.945668 | 0.958523 | 0.979353 | 0.959349 | 1.007231 | 0.93932 | 1.009748 |
| T 54 | 0.96215 | 0.937208 | 0.9 | 1.010499 | 1.017764 | 0.949718 | 0.949325 | 1.03725 |
| T 58 | 0.978117 | 0.985567 | 1.09296 | 0.977078 | 1.019769 | 1.011276 | 1.002978 | 0.932774 |
| T 59 | 1.009475 | 0.970196 | 1.031525 | 0.987578 | 1.001157 | 0.936331 | 0.987746 | 0.945577 |
| T 65 | 0.990709 | 0.996095 | 0.9 | 0.999182 | 1.018785 | 1.012632 | 0.907788 | 0.94514 |
| T 66 | 0.929315 | 0.949284 | 0.913771 | 0.944544 | 0.915771 | 0.939471 | 0.926532 | 0.981624 |
| T 71 | 0.961921 | 1.005442 | 1.006757 | 0.99327 | 0.951879 | 0.986018 | 0.935725 | 0.935201 |
| T 73 | 0.955812 | 0.950852 | 1.028959 | 0.953538 | 0.963954 | 0.902311 | 0.910316 | 1.002568 |
| T 76 | 0.960738 | 0.954664 | 1.1 | 0.976423 | 0.928242 | 0.962383 | 0.965958 | 1.001981 |
| T 80 | 0.989151 | 0.997386 | 0.988844 | 0.95528 | 1.022631 | 0.992455 | 1.011384 | 0.995795 |
| Q 3 | 3.3741 | 4.401428 | 4.137971 | 4.440792 | 4.523823 | 4.550052 | 4.484197 | 2.994497 |
| Q 25 | 2.03254 | 1.46774 | 2.024791 | 2.193283 | 1.758374 | 2.417182 | 1.431282 | 2.107172 |
| Q 53 | 3.125171 | 3.362089 | 0.911122 | 3.538278 | 2.370584 | 4.464291 | 4.124964 | 2.653132 |

According to the base case $3.737016 \times 10^6$($), the outcomes of the different optimization techniques are compared as follows. LAPO is 36.2620 %, PSO is 29.3902 %, ALO is 32.9599 %, EO is 36.1709 %, MPA is 34.7849 %, WOA is 34.7634 %, SCA is 31.7022% while MLAPO is 36.88012 %. Moreover, to further validate the performance of MLAPO, *OC* values reported by the different optimization techniques are cited as follows. PSO-EE [38] is 27.8328%, FOPSO-EE [38] is 28.2609%, QODE [2] is 25.7295%, QOGWO [2] is 10.9477%, WOA [2] is 10.9209%, SPSO [69] is 26.8828%, EPSO [69] is 36.6580% and APSO [69] is 36.9604%. The optimal sizes and placements of TCSCs and SVCs are given in Table. 11. While, the control variables are provided in X. The overall simulation results demonstrated the best performance achieved by MLAPO to reduce the *OC* with optimal allocation of the FACTS devices on IEEE 30-bus standard.

### B. CONSIDERING WITH AND WITHOUT OPTIMAL ALLOCAITON OF FACTS DEVICES USING IEEE 57-BUS STANDARD

The IEEE 57-bus standard consisting of six generators 1, 2, 3, 6, 8, 9 and 12, fifteen transformers tap settings with three shunts compensators while bus 1 is selected as slack bus. The base 100 MVA with total demands of active and reactive powers for this case are 12.5170 MW and 3.3570 MVAr, respectively. In case of considering FACTS devices, the base case of active *Plosses* and operating cost are taken as 27.99 MW and $1.471 \times 10^7$($), respectively. While, the base case is taken as 27.86 MW for *Plosses* [70] and *VD* is 4.1788 p.u. [59] without considering FACTS devices.

The section B is categorized in further five sub-sections using IEEE57 bus-standard with and without optimal inclusion TCSC and SVC. The details of sub-sections are given below.

1. Minimization of Power Losses without optimal allocation of the FACTS Devices
2. Minimization of Voltage Deviation without optimal allocation of the FACTS Devices
3. Minimization of Power Losses with optimal allocation of the FACTS Devices
4. Minimization of Voltage Deviation with optimal allocation of the FACTS Devices
5. Minimization of Overall Operating Cost with optimal allocation of the FACTS Devices

The selection of the parameters and the limits of the control variables are taken from Table. 1 and 12.

**TABLE 18. Output Of control variables with TCSC and SVC for minimizing the power losses (MW) using IEEE57 bus standard.**

| C-Variables | LAPO | MLAPO (Proposed) | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| V (1) | 1.099592 | 1.099082 | 1.1 | 1.098227 | 1.1 | 1.099998 | 1.099925 | 1.1 |
| V (2) | 1.097195 | 1.089027 | 1.1 | 1.099904 | 1.096983 | 1.092103 | 1.1 | 1.1 |
| V (3) | 1.09877 | 1.092571 | 1.1 | 1.099895 | 1.098015 | 1.099587 | 1.08468 | 1.094739 |
| V (6) | 1.087137 | 1.091679 | 1.082308 | 1.036141 | 1.063064 | 1.08475 | 1.074757 | 1.1 |
| V (8) | 1.098633 | 1.090791 | 1.1 | 1.087853 | 1.1 | 1.099999 | 1.093415 | 1.1 |
| V (9) | 1.093709 | 1.088116 | 1.1 | 1.063929 | 1.08938 | 1.096751 | 1.048964 | 1.1 |
| V (12) | 1.093259 | 1.081531 | 1.1 | 1.076089 | 1.071199 | 1.082815 | 1.07084 | 1.089004 |
| T 19 | 1.097595 | 1.070568 | 1.1 | 1.053071 | 0.944765 | 1.073367 | 1.077084 | 1.1 |
| T 20 | 1.1 | 1.073117 | 1.1 | 1.074422 | 1.052031 | 0.953484 | 1.099644 | 1.1 |
| T 31 | 1.06448 | 1.057801 | 1.1 | 1.055507 | 1.09812 | 1.03726 | 1.096249 | 0.9 |
| T 35 | 1.002252 | 1.038507 | 0.9 | 1.099862 | 0.990065 | 0.99967 | 1.062968 | 0.9 |
| T 41 | 1.07771 | 1.08337 | 0.9 | 1.064614 | 0.911369 | 0.905885 | 0.940927 | 0.9 |
| T 46 | 0.956673 | 1.03756 | 0.9 | 1.019143 | 0.908683 | 0.92815 | 0.94357 | 1.1 |
| T 54 | 1.094367 | 1.092629 | 1.1 | 1.059337 | 1.098562 | 0.990926 | 0.900346 | 0.9 |
| T 58 | 1.080145 | 1.042918 | 0.99302 | 1.023624 | 0.902874 | 0.924237 | 0.914039 | 1.1 |
| T 59 | 1.077788 | 1.029606 | 0.991607 | 1.054472 | 0.901327 | 0.904057 | 0.903792 | 1.1 |
| T 65 | 1.083307 | 1.085334 | 0.989418 | 1.04946 | 0.914091 | 0.903729 | 0.901807 | 1.1 |
| T 66 | 1.08436 | 1.007111 | 0.965036 | 1.050708 | 0.902269 | 0.901724 | 0.900945 | 1.1 |
| T 71 | 1.094826 | 1.098181 | 1.1 | 1.098295 | 0.900222 | 0.906238 | 0.962869 | 1.1 |
| T 73 | 1.062197 | 1.097055 | 1.1 | 1.099527 | 1.098917 | 1.017786 | 1.059848 | 1.1 |
| T 76 | 0.914669 | 1.09216 | 0.9 | 1.07795 | 1.041074 | 1.024426 | 0.977694 | 1.1 |
| T 80 | 1.093228 | 1.092078 | 0.9 | 1.040694 | 0.900623 | 0.90056 | 0.947991 | 0.9 |
| Q 3 | 0.010846 | 0.239832 | 0 | 1.244698 | 2.422576 | 1.984474 | 3.680106 | 0 |
| Q 25 | 0.872557 | 0.71212 | 1.695839 | 1.366721 | 1.461641 | 1.99904 | 1.093275 | 2.107499 |
| Q 53 | 1.44822 | 1.089554 | 1.481344 | 2.020616 | 1.570864 | 2.00666 | 1.435508 | 1.456929 |

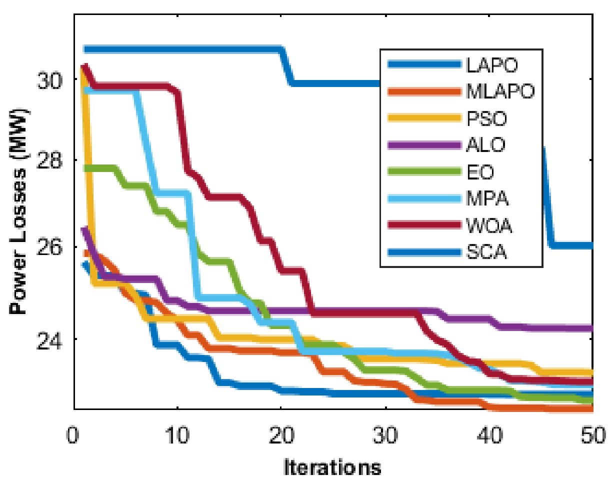


**FIGURE 10. Minimization of power losses without optimal allocation of FACTS using IEEE57 standard.**

### 1) MINIMIZATION OF POWER LOSSES WITHOUT OPTIMAL ALLOCATION OF THE FACTS DEVICES

In this case, the consideration of FACTS devices using TCSC and SVC aims to minimize the *Plosses* The simulation outcomes of the different considered algorithms including MLAPO are given in Table. 13 with their average, worst and best values. Fig. 10 demonstrated the best convergence response attained by MLAPO with 22.6081 MW, while the worst response attained by SCA with 26.0042 MW.

The base case is 27.86 MW. In the aspect of reduction of *Plosses*, the different optimization techniques given in Table. 13 are compared to the base case. LAPO is 17.85%, PSO is 16.31%, ALO is 13.04%, EO is 18.26%, MPA is 17.17%, WOA is 16.93 % and SCA is 6.66% while MLAPO is 18.85%. In addition, to validate the performance of MLAPO, the other well-known optimization techniques given in Table. 14 are further compared with the base case. ALO is 13.49%, AGA is 11.84%, ICA is 2.64%, FPSOGSA is 17.74%, CBA-IV is 21.68%, MPSO is 15.61%, PSO-EE is 5.02%, PFA is 11.43%, CBA-III is 20.97%, ICA-PSO is 2.39%, FODPSO is 4.23%, PSO is 0.06%, FA-APTFPSO-IV is 13.54%, CGA is 13.01% and FOPSO-EE is 5.10%.

The best values of control variables against the minimization of *Plosses* are reported in Table. 16. Fig. 10, Table. 13 and 16 endorse the best efficiency of MLAPO to reduce $P_{losses}$ without optimal allocations of the FACTS devices.

### 2) MINIMIZATION OF VOLTAGE DEVIATION WITHOUT OPTIMAL ALLOCATION OF THE FACTS DEVICES

The 2$^{nd}$ objective for this case is to minimize *VD* without optimal allocations of the FACTS devices using IEEE 57-bus. The simulation results can be seen in Table. 12, yielded by MLAPO along the comparison to the other optimization techniques, such as LAPO, PSO, ALO, EO, MPA, WOA and

**TABLE 19. Output of control variables with TCSC and SVC for minimizing the voltage deviation (p.u) using IEEE57 bus standard.**

| Control Variables | LAPO | MLAPO | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| V (1) | 1.019835 | 0.990917 | 1.01366 | 1.024523 | 1.028861 | 1.027188 | 1.009753 | 0.974322 |
| V (2) | 1.000713 | 1.012784 | 1.025047 | 0.970913 | 0.992338 | 1.036515 | 1.018614 | 0.935622 |
| V (3) | 1.002434 | 1.034085 | 0.980577 | 1.003732 | 1.041539 | 1.009874 | 1.002708 | 1.1 |
| V (6) | 1.000366 | 1.006945 | 1.037231 | 1.035364 | 1.001945 | 1.012981 | 0.995121 | 1.057671 |
| V (8) | 1.00544 | 1.04364 | 0.994523 | 1.006366 | 0.986939 | 1.002987 | 1.008186 | 1.065845 |
| V (9) | 1.011351 | 1.040369 | 1.03653 | 0.961888 | 0.928823 | 1.00998 | 1.004238 | 1.1 |
| V (12) | 1.022414 | 1.020733 | 1.035892 | 1.029485 | 1.047009 | 0.99702 | 1.049864 | 1.002136 |
| T 19 | 0.969279 | 1.018165 | 1.013189 | 0.984735 | 0.954429 | 0.953227 | 1.026229 | 1.06529 |
| T 20 | 1.016275 | 1.038839 | 1.074681 | 0.97822 | 1.062865 | 1.078814 | 0.92538 | 1.017042 |
| T 31 | 0.970709 | 1.056221 | 0.937056 | 0.990655 | 0.966278 | 0.961897 | 0.989335 | 0.989329 |
| T 35 | 0.988446 | 1.007669 | 1.038699 | 0.99276 | 0.951254 | 0.976481 | 1.019985 | 1.023486 |
| T 41 | 1.006153 | 1.041536 | 1.017524 | 0.975595 | 1.008901 | 1.011779 | 0.975874 | 1.074814 |
| T 46 | 0.971199 | 0.978457 | 0.915989 | 0.99063 | 0.92501 | 0.964438 | 0.932986 | 0.996709 |
| T 54 | 0.964496 | 0.946504 | 0.9 | 0.998387 | 1.020109 | 0.931185 | 0.982897 | 0.912865 |
| T 58 | 1.01407 | 0.995671 | 1.057454 | 1.026428 | 1.021929 | 1.021807 | 1.019639 | 1.1 |
| T 59 | 0.967568 | 1.052983 | 1.059671 | 0.995024 | 0.967384 | 0.968193 | 0.97792 | 0.966574 |
| T 65 | 0.977997 | 1.041745 | 0.929786 | 1.008724 | 0.956926 | 0.973406 | 0.987101 | 0.958053 |
| T 66 | 1.021635 | 0.91362 | 0.9 | 0.952478 | 0.997891 | 0.940184 | 0.929287 | 1.059161 |
| T 71 | 0.991787 | 0.955739 | 1.029109 | 0.968024 | 0.936159 | 0.993711 | 0.975469 | 1.026947 |
| T 73 | 0.960938 | 0.929159 | 0.912358 | 0.962116 | 0.900001 | 0.96816 | 0.928986 | 1.04958 |
| T 76 | 0.992926 | 1.004379 | 0.993483 | 1.006704 | 0.994845 | 0.93266 | 0.916974 | 0.954055 |
| T 80 | 0.99772 | 0.989644 | 0.915247 | 0.992773 | 0.929456 | 0.963832 | 1.010949 | 0.995623 |
| Q 3 | 3.037278 | 3.345555 | 5 | 1.766866 | 4.814162 | 3.275209 | 2.427896 | 4.117299 |
| Q 25 | 2.07301 | 1.902842 | 0.929586 | 2.268187 | 1.207016 | 2.011866 | 0.904739 | 2.017572 |
| Q 53 | 3.416284 | 2.975187 | 1.777256 | 2.269169 | 3.037079 | 2.659809 | 3.862978 | 2.794869 |

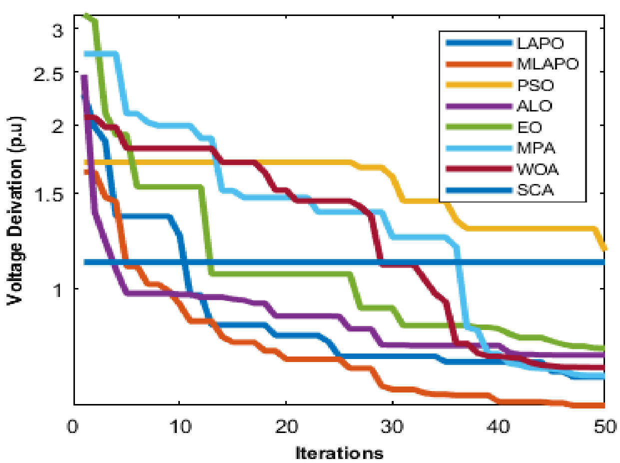


**FIGURE 11. Minimization of power losses without optimal allocation of FACTS devices using IEEE57 standard.**

SCA. Fig. 11 illustrated the best performance achieved by MLAPO with 0.6111 p.u. while the worst case obtained by PSO with 1.737 p.u.

In case of reduction in *VD*, the outcomes of some other optimization techniques given in Table. 13 are compared to the base case 4.1788 p.u. LAPO is 83.50%, PSO is 58.43%, ALO is 81.91%, EO is 81.39%, MPA is 83.42%, WOA is 82.83%, SCA is 73.23%, while MLAPO is reported as 85.38%, respectively.

To validate the performance, MLAPO is further compared to well-known techniques given in Table. 15. For example, CLPSO is 73.85%, ICA is 80.97%, ICA-PSO is 82.94%, SGA(Ff1) is 35.34%, PSO is 80.84% and FODPSO is 83.00%, respectively. The best control variable outcomes against the *VD* are given in Table. 17. Fig. 11, Table. 13 and 17 demonstrated the best response computed by MLAPO.

### 3) MINIMIZATION OF POWER LOSSES WITH OPTIMAL ALLOCATION OF THE FACTS DEVICES

In this case, the simulation is carried out for minimization of *Plosses* without optimal allocations of the TCSC and SVC using IEEE 57-bus standard. In Table. 13, the simulation outcomes can be seen in case of minimizing the *Plosses* yielded by MLAPO, along the comparison with other considered optimization techniques, such as LAPO, PSO, ALO, EO, MPA, WOA and SCA. Fig. 12 illustrated the best convergence response achieved by MLAPO technique with 21.4448 MW while the worst case computed by SCA with 25.0183 MW.

**TABLE 20. Output of control variables with TCSC and SVC for minimizing the operating cost in ($) using IEEE57 bus standard.**

| Control Variables | LAPO | MLAPO (Proposed) | PSO | ALO | EO | MPA | WOA | SCA |
|---|---|---|---|---|---|---|---|---|
| V (1) | 1.1 | 1.09994 | 1.1 | 1.097233 | 1.099897 | 1.09998 | 1.099984 | 1.1 |
| V (2) | 1.098949 | 1.099616 | 1.1 | 1.095826 | 1.091977 | 1.093022 | 1.099993 | 1.1 |
| V (3) | 1.099877 | 1.09875 | 1.1 | 1.093129 | 1.088584 | 1.097437 | 1.098104 | 1.1 |
| V (6) | 1.099245 | 1.1 | 1.1 | 1.097558 | 1.094436 | 1.096568 | 1.094273 | 1.1 |
| V (8) | 1.099686 | 1.092884 | 1.1 | 1.085832 | 1.099551 | 1.099995 | 1.099705 | 1.1 |
| V (9) | 1.074785 | 1.096313 | 1.1 | 1.064942 | 1.092797 | 1.096737 | 1.025227 | 1.08477 |
| V (12) | 1.08091 | 1.073392 | 1.1 | 1.074092 | 1.074746 | 1.086258 | 1.076789 | 1.1 |
| T 19 | 1.085647 | 1.052923 | 1.1 | 1.081669 | 0.964113 | 0.976801 | 0.993956 | 0.9 |
| T 20 | 1.093266 | 1.098837 | 1.1 | 1.097168 | 0.920784 | 0.954386 | 0.900269 | 0.9 |
| T 31 | 1.097881 | 1.1 | 1.1 | 1.017873 | 1.012514 | 1.028086 | 1.020769 | 0.9 |
| T 35 | 0.9 | 0.9 | 1.1 | 1.08088 | 0.979071 | 1.002379 | 1.036024 | 1.094276 |
| T 41 | 0.9 | 0.905415 | 0.971868 | 1.040368 | 0.904934 | 0.90654 | 0.942108 | 1.1 |
| T 46 | 0.937084 | 0.999985 | 0.9 | 0.994187 | 0.977755 | 0.900756 | 1.022706 | 0.932813 |
| T 54 | 0.9 | 1.098991 | 1.1 | 1.09763 | 0.930881 | 0.996302 | 0.944959 | 0.9 |
| T 58 | 1.002474 | 1.04301 | 0.9 | 1.054103 | 0.923231 | 0.914263 | 0.904802 | 0.9 |
| T 59 | 0.992094 | 1.01444 | 0.9 | 1.040681 | 0.919014 | 0.905565 | 0.900455 | 0.987351 |
| T 65 | 0.982222 | 1.029402 | 0.9 | 1.05265 | 0.912888 | 0.915878 | 0.910853 | 0.998612 |
| T 66 | 0.982403 | 1.031693 | 0.9 | 1.054999 | 0.908546 | 0.901572 | 0.900839 | 0.9 |
| T 71 | 0.983597 | 1.04928 | 0.9 | 1.056121 | 0.927938 | 1.08366 | 0.953098 | 0.989557 |
| T 73 | 0.951351 | 1.090083 | 1.1 | 1.023041 | 1.003576 | 1.065693 | 1.021654 | 1.003073 |
| T 76 | 0.905744 | 0.921927 | 1.1 | 1.063113 | 0.987003 | 1.072975 | 0.965258 | 0.9 |
| T 80 | 0.9 | 0.9 | 0.961808 | 1.056394 | 0.904667 | 0.911531 | 0.933251 | 1.1 |
| Q 3 | 0.04237 | 0.644112 | 0 | 1.483579 | 1.548384 | 0.076277 | 0.957916 | 0.362263 |
| Q 25 | 1.058776 | 0.809463 | 1.186636 | 1.867191 | 0.776682 | 1.062296 | 1.88E-06 | 1.065238 |
| Q 53 | 1.505423 | 1.409129 | 1.319174 | 1.724377 | 1.128296 | 0 | 1.940405 | 0 |

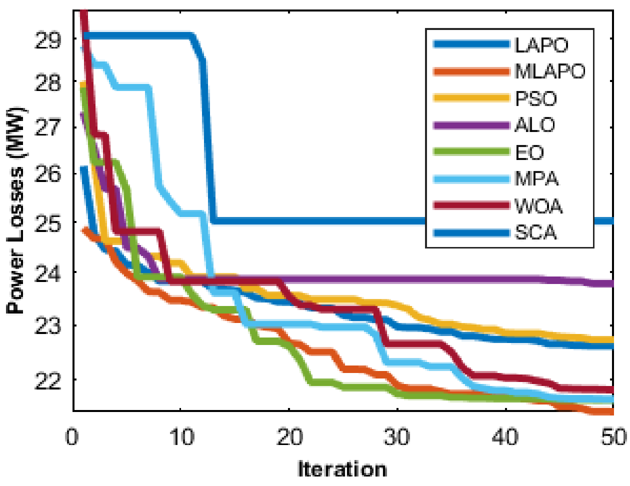


**FIGURE 12. Minimization power losses optimal allocation of FACTS devices using IEEE57 standard.**

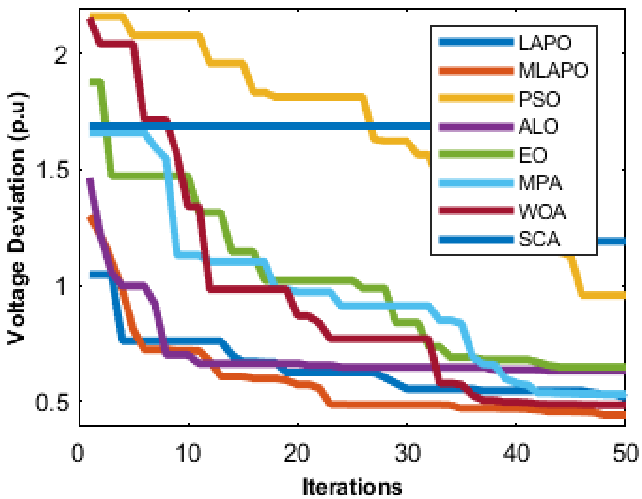


**FIGURE 13. Minimization voltage deviation optimal allocation of FACTS devices using IEEE57 standard.**

In case of reduction in Plosses, the simulation results of the considered optimization techniques including MLAPO given in Table. 13 are compared to the base case 27.99 MW.

LAPO is 19.1901 %, PSO is 18.79 %, ALO is 15.03 %, EO is 22.66 %, MPA is 22.60 %, WOA is 21.99 %, SCA is 10.62 % and MLAPO is reported as 23.38 %. While compare to the based case 27.86 MW, the MLAPO is reported 23.26 % less than with considering TCSC and SVC.

In order to further ensure the performance of MLAPO, the other well-known optimization techniques are also compared APSO [69] is 20.29% and EPSO [69] is 18.72%, respectively. The optimal sizes and placements of TCSCs and SVCs are given in Table. 21. While, the control variables are provided in XVIII. Fig. 12 and Table. 13 demonstrated the best performance computed by MLAPO.

**TABLE 21. Optimal allocations and sizes of TCSC and SVC for different considered objective functions using IEEE57 bus standard.**

| | | Parameters | TCSC1 | TCSC2 | TCSC3 | TCSC4 | SVC1 | SVC2 | SVC3 | SVC4 |
|---|---|---|---|---|---|---|---|---|---|---|
| LAPO | Plosses | Size (p.u) | 0.051168 | 0.000695 | 0.013717 | 0.000956 | 0.037226 | 0.2 | 0.060779 | 0.175687 |
| | | Location | 70 | 47 | 72 | 65 | 57 | 1 | 2 | 49 |
| | VD | Size (p.u) | 0.027993 | 0.038194 | 0.045007 | 0.025129 | 0.06691 | 0.078108 | 0.13498 | 0.1084 |
| | | Location | 38 | 49 | 34 | 37 | 33 | 24 | 17 | 29 |
| | *OC* | Size (p.u) | 0.019345 | 0 | 0.007886 | 0.009512 | 0.008366 | 0.087439 | 0.139888 | 0.161491 |
| | | Location | 1 | 80 | 1 | 1 | 6 | 10 | 55 | 57 |
| MLAPO | Plosses | Size (p.u) | 0.003499 | 0.031165 | 0.066839 | 0.010054 | 0.057654 | 0.148966 | 0.125141 | 0.10672 |
| | | Location | 54 | 77 | 73 | 23 | 19 | 4 | 55 | 23 |
| | VD | Size (p.u) | 0.051178 | 0.057284 | 0.033432 | 0.044538 | 0.06062 | 0.121403 | 0.11963 | 0.115471 |
| | | Location | 69 | 34 | 51 | 35 | 31 | 37 | 12 | 39 |
| | *OC* | Size (p.u) | 0.066064 | 0.042494 | 0.049089 | 0.008073 | 0.127797 | 0.02015 | 0.181706 | 0.120234 |
| | | Location | 1 | 2 | 4 | 36 | 5 | 53 | 55 | 57 |
| PSO | Plosses | Size (p.u) | 0.08 | 0.08 | 0.08 | 0.08 | 0 | 0.2 | 0.2 | 0.2 |
| | | Location | 80 | 43 | 10 | 27 | 23 | 19 | 23 | 26 |
| | VD | Size (p.u) | 0.059488 | 0.045619 | 0.024803 | 0.077402 | 0 | 0.045144 | 0.2 | 0.101471 |
| | | Location | 45 | 54 | 67 | 40 | 48 | 46 | 42 | 42 |
| | *OC* | Size (p.u) | 0.08 | 0 | 0 | 0 | 0.2 | 0.2 | 0 | 0.10907 |
| | | Location | 61 | 40 | 37 | 38 | 40 | 29 | 12 | 1 |
| ALO | Plosses | Size (p.u) | 0.047615 | 0.072257 | 0.058807 | 0.036071 | 0.069522 | 0.051648 | 0.135019 | 0.093629 |
| | | Location | 67 | 43 | 49 | 31 | 35 | 40 | 51 | 25 |
| | VD | Size (p.u) | 0.053644 | 0.037327 | 0.038567 | 0.032449 | 0.17235 | 0.121795 | 0.11570 | 0.147059 |
| | | Location | 42 | 49 | 42 | 22 | 33 | 38 | 41 | 35 |
| | *OC* | Size (p.u) | 0.036152 | 0.019507 | 0.02169 | 0.013256 | 0.036414 | 0.089176 | 0.120185 | 0.103064 |
| | | Location | 48 | 33 | 13 | 24 | 36 | 24 | 22 | 21 |
| EO | Plosses | Size (p.u) | 0.007527 | 0.050243 | 0.00894 | 0.019397 | 0.000743 | 0.016071 | 0.028984 | 0.018533 |
| | | Location | 25 | 59 | 29 | 58 | 11 | 2 | 5 | 57 |
| | VD | Size (p.u) | 0.079823 | 0 | 0.073787 | 0.038544 | 0.17115 | 0.102155 | 0.11223 | 0.057561 |
| | | Location | 53 | 73 | 29 | 80 | 54 | 3 | 15 | 34 |
| | *OC* | Size (p.u) | 0.025934 | 0.020858 | 0.056562 | 0.002581 | 0.0107 | 0.125039 | 0.124167 | 0.06925 |
| | | Location | 66 | 26 | 71 | 5 | 13 | 43 | 40 | 9 |
| MPA | Plosses | Size (p.u) | 0.052705 | 0.023896 | 0.06034 | 0.022684 | 0.032555 | 0.059469 | 0.076882 | 0.145239 |
| | | Location | 47 | 58 | 45 | 40 | 14 | 2 | 34 | 2 |
| | VD | Size (p.u) | 0.049507 | 0.015426 | 0.024419 | 0.042605 | 0.08724 | 0.098419 | 0.12266 | 0.039648 |
| | | Location | 31 | 46 | 16 | 35 | 24 | 21 | 27 | 36 |
| | *OC* | Size (p.u) | 0.048703 | 0.012461 | 0.00148 | 0.0083 | 0.096074 | 0.046065 | 0.199502 | 0.123422 |
| | | Location | 1 | 73 | 1 | 2 | 6 | 8 | 17 | 17 |
| WOA | Plosses | Size (p.u) | 0.013343 | 0.037859 | 0.079996 | 0.03045 | 0.090259 | 0.144615 | 0.046621 | 0 |
| | | Location | 79 | 44 | 79 | 32 | 56 | 57 | 30 | 57 |
| | VD | Size (p.u) | 0.029481 | 0.041523 | 0.053135 | 0.037791 | 0.07589 | 0.062606 | 0.10167 | 0.122267 |
| | | Location | 56 | 33 | 64 | 44 | 45 | 43 | 22 | 36 |
| | *OC* | Size (p.u) | 0.034708 | 0.041305 | 0.061075 | 0.076497 | 0.024048 | 0.198131 | 0.04455 | 0.199755 |
| | | Location | 2 | 1 | 10 | 1 | 31 | 10 | 1 | 35 |
| SCA | Plosses | Size (p.u) | 0.001524 | 0.002391 | 0.026008 | 0.08 | 0 | 0.176759 | 0.138982 | 0.069137 |
| | | Location | 7 | 73 | 1 | 2 | 57 | 54 | 1 | 1 |
| | VD | Size (p.u) | 0.018522 | 0.034946 | 0 | 0.075174 | 0.16620 | 0.060727 | 0.13507 | 0.105882 |
| | | Location | 18 | 79 | 3 | 6 | 38 | 53 | 1 | 3 |
| | *OC* | Size (p.u) | 0 | 0 | 0.022559 | 0 | 0 | 0.078742 | 0.175121 | 0.024059 |
| | | Location | 24 | 5 | 7 | 1 | 57 | 2 | 12 | 43 |

#### 4) MINIMIZATION OF VOLTAGE DEVIATION WITH OPTIMAL ALLOCATION OF THE FACTS DEVICES

The objective of this case is to minimize the *VD* to improve voltage profile with optimal allocation of the FACTS devices according to IEEE 57-bus standard.

MLAPO with other optimization techniques are considered while running the simulations. The simulation outcomes are given in Table. 13. They include the average, best and worst values of *VD*.

Fig. 13 demonstrated the best performance achieved by MLAPO with 0.4383 p.u. while the worst case reported by SCA with 1.1906 p.u. In case of reduction in *VD*, the result computed by MLAPO is less than that of other optimization techniques given in Table. 13. For example, LAPO is 14.84 %, PSO is 54.24 %, ALO is 30.45 %, EO is 32.28 %, MPA is 17.19 %, WOA is 9.23 % and SCA is 63.19 %. The optimal sizes and placements of TCSCs and SVCs are given in Table. 21. While, the control variables are provided in XIX. Fig. 13 and Table. 13 endorsed the best performance of MLAPO using FACTS devices.

#### 5) MINIMIZATION OF OVERALL OPERATING COST WITH OPTIMAL ALLOCATION OF THE FACTS DEVICES

To minimize the *OC* of optimal allocation of FACTS devices, the simulations are performed on different algorithms where the parameter values and restraints of the control variables are taken from Table. 1 and Table. 12. Fig. 14 illustrated the best convergence response achieved by MLAPO with $1.1165 \times 10^7$($) whereas the worst response reported by ALO with *OC* value $1.2768 \times 10^7$($).

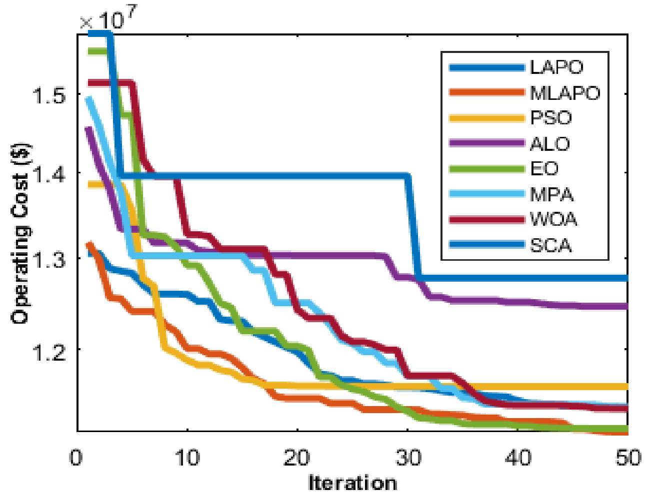


**FIGURE 14. Minimization of operating cost optimal allocation of FACTS devices using IEEE57 standard.**

The simulation outcomes reported for the different algorithms including MLAPO are given in Table. 13 with their average, best and the worst values. The base case is considered $1.471 \times 10^7$ in order to compared the performance of the different considered algorithms including MLAPO. Judging from Table. 13, the reduction in *OC* are reported as follows. LAPO is 22.54 %, PSO is 21.03 %, ALO is 15.32 %, EO is 23.87 %, MPA is 22.40 %, WOA is 22.52 %, SCA is 13.20 % whereas MLAPO 24.01 %. In order to further validate the performance of MLAPO, the other well-known optimization techniques are also compared. SPSO [69] is 20.59%, APSO [69] is 19.85% and EPSO [69] is 18.22%. The optimal sizes and placements of TCSCs and SVCs are given in Table. 21. While, the control variables are provided in XX. Fig. 14 and Table. 13 demonstrated the best performance achieved by MLAPO to reduce the *OC* using FACTS devices.

## VI. CONCLUSION

In this paper, ORPD including SVC and TCSC has been solved using MLAPO. The exploration and exploitation phases of the conventional LAPO are improved based on new movement of the particles using levy flight distribution and spiral orientation motion. The objective functions are power loss reduction, voltage profile improvement, and cost minimization. The impact of incorporating SVC and TCSC, and performance of the algorithm have been verified through the IEEE 30-bus and IEEE 57-bus systems.

Compared to those without the FACTS devices, the simulation reveals that the optimal allocation of the controllers reduced the power loss and operating cost, improve the voltage profile considerably. Furthermore, the algorithm is better for ORPD compared with the previous LAPO, PSO, ALO, EO, MPA, WOA and SCA.

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