A novel tree seed algorithm for optimal reactive power planning and reconfiguration based STATCOM devices and PV sources

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Abstract

Reactive power dispatch based on static synchronous compensator (STATCOM) and photovoltaic (PV) sources in coordination with reconfiguration strategy is vital task to ensure reliable operation of modern radial distribution (RD) systems. This paper introduces a novel tree seed algorithm (TSA) to improve the performance of modern RD power systems. A variant of TSA based on intelligent and flexible mechanism search is proposed to create an interactive equilibrium between exploration and exploitation during the search process to improve the global solution. Two objective functions, the total power loss and the margin reserve security are optimized under normal condition and critical load growth. To obtain reliable operation of the distribution system under critical situations, a reactive power dispatch based STATCOM devices is managed in coordination with the reconfiguration stage to find the best combination of sectionalizing switches and tie switches to be operated. The efficiency and particularity of the proposed distribution-planning strategy validated on two test systems, the radial 33 buses and the practical radial 250 buses (30 kV) of Sonelgaz Company located in Biskra in the south of Algeria. This radial electric network designed principally to deliver energy to several small and important agricultural consumers. Results obtained based on various test cases and scenarios using the proposed new planning strategy confirm the efficiency of the proposed planning strategy in terms of reduction of the total power loss, improvement voltage magnitude and enhancement of margin reserve.

Keywords Reconfiguration · Tree seed algorithm · Radial distribution electric system · Reactive power planning · STATCOM · Power loss · PV source

List of symbols

$P_{loss(k,k+1)}$	Active power loss between bus k and bus k + 1	$Obj1$	Objective function related to total power loss
$Q_{loss(k,k+1)}$	Active power loss between bus k and bus k + 1	$Obj2$	Objective function related to margin reserve
$R_{k,k+1}, X_{k,k+1}$	Resistance and reactance of line located between bus k and bus k + 1	MR	Margin reserve
$P_{k,k+1}, Q_{k,k+1}$	Active and reactive power flow at line located between bus k and bus k + 1	$P_{tr,slack}, Q_{tr,slack}$	Active and reactive power of slack transformer
V_k	Voltage magnitude at bus k	$P_{D,i}, Q_{D,i}$	Active and reactive power load demand in the bus i
U_{max}, U_{min}	Maximum and minimum voltage magnitude.	V_i^{min}, V_i^{max}	Minimum and maximum voltage at bus i
$P_{t,loss}$	Total power loss.	nbr	Number of lines
		N_{pv}	Number of PV bus
		$P_{pv,i}$	Active power delivered by PV source at bus i

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$Q_{pv,i}$	Reactive power delivered by PV source at bus i
$p_{pv,i}^{\min}$	Minimum limit of active power delivered by PV source located at bus i
$p_{pv,i}^{\max}$	Maximum limit of active power delivered by PV source located at bus i
μ	Penetration level of PV source
$Q_{Stc,i}$	Reactive power delivered by STATCOM device at bus i .
$Q_{Stc,i}^{\min}$	Minimum reactive power delivered by STATCOM device at bus i .
$Q_{Stc,i}^{\max}$	Maximum reactive power delivered by STATCOM device at bus i .
I_{bri}	Current flow in line i
$I_{bri}^{\max}$	Maximum current flow in line i
P_{ij}, Q_{ij}	Active and reactive power flow at lines
R_{ij}, X_{ij}	Resistance and reactance of line connected between bus i and bus j
U_i	Voltage magnitude at bus i
dU_{ij}	Voltage drop between bus i and bus j before compensation
dU_{ij}^c	Voltage drop between bus i and bus j after compensation
Q_{ij}^c	Reactive power flow between bus i and bus j after compensation
S_{ij}^o	Apparent power flow between bus i and bus j before compensation
S_{ij}^n	New apparent power flow between bus i and bus j after compensation
$\cos(\phi_o)$	Power factor before compensation
$\cos(\phi_n)$	Power factor after compensation
KI	Loading factor
$I_{C\max}$	Maximum capacitive current
$I_{L\max}$	Maximum inductive current
$\alpha_{\max}, \alpha_{\min}$	Maximum and minimum firing angle
V_{ref}	Reference voltage

Abbreviations

FACTS	A flexible alternating current transmission system
STATCOM	Static synchronous compensator
RD	Radial distribution.
RS	Renewable source
PV	Photovoltaïque source
TSA	Tree seed algorithm
RPP	Reactive power planning
RPD	Reactive power dispatch
SW	Sectionalizing switch
TW	Tie switch
PF	Power flow
BPSO	Binary Particle Swarm Optimization
STATCOM	Static synchronous compensator

D-STATCOM	Distributed static synchronous compensator
OLTC	On-Load Tap Changer

1 Introduction

Ensuring reliable operation of modern radial distribution (RD) systems is a vital challenge for utility companies and experts specialized in power system planning and operation. Due to the economic aspect, most electrical distribution systems have radial structure. This topology has low investment cost, easy to dispatch and power system protection is not complex. Otherwise, the operation of radial topology without adequate energy management cannot guaranty sufficient energy quality and service continuity in particular at critical situations such as load growth and faults. Recently with large diffusion in electricity market of flexible ac transmission system (FACTS) and various types of renewable sources such as wind energy, solar energy and fuel cell sources, the modern distribution power system becomes more flexible to control and to dispatch, which allows improving the quality of energy and service continuity [1]. Otherwise, the main drawback of integration of various types of renewable sources such as wind and PV sources in RD systems is related to their intermittent behavior. The integration of renewable sources needs robust planning strategies to improve the performance of RD systems in terms of reduction of total power losses, improvement the voltage magnitudes and improvement the margin reserve security [2].

In the literature, various planning strategies based on analytical methods, metaheuristic and hybrid methods have been developed and used to improve the performances of modern radial distribution systems considering the integration of various types of renewable sources [3]. These developed techniques have been applied to solve three categories of optimal planning of RD systems. The first research target has been oriented to find the optimal allocation and size of conventional bank capacitors [3] in RD systems. The second research objective is investigated to optimize the size and location of distribution generation (DG) in coordination with bank compensators [3, 4], and finally, the third target focuses on the optimal reconfiguration of modern radial distribution systems by optimizing the number and location of multi-switch to be operated in the presence of multi-DG and shunt compensators [5]. Among these techniques, authors in [6] applied a novel approach based on crow search algorithm for optimal selection of conductor size in radial distribution networks, in [7] a mixed integer nonlinear programming approach is applied to solve the optimal location of bank capacitors in radial distribution systems, in [8] an analytical

approach is applied to solve the optimal location of distributed generation and bank capacitors for power loss minimization, in [9] a hybrid heuristic search optimization technique is applied to solve the optimal location and size of distributed generators and shunt compensators, in [10] a selective firefly algorithm is applied to solve the distribution network reconfiguration to minimize total power loss, in [11] a multi-objective evolutionary algorithm based on decomposition (MOEA/D) is adapted to select optimal sizes and locations of DGs and shunt compensator in large scale RD networks, in [12] an interactive methodology is applied to solve the optimal placement of multi-period-based switched capacitor in radial distribution electric system, in [13] an improved selective binary particle swarm optimization (BPSO) is applied to solve the network reconfiguration for loss reduction, in [14] an improved shuffled frog leaping is used to solve the reconfiguration problem in radial distribution system in the presence of multi-distributed generation (DG), the impact of reconfiguration strategy on the power loss reduction in practical radial distribution system is well demonstrated in [15]. Considered as a new research direction, authors in [16] applied fast metaheuristic algorithms for optimal reconfiguration in radial distribution system to reduce the number of harmonics. In [17] a hybrid planning strategy reduction in radial distribution system based on the reconfiguration procedure and optimal control of On-Load Tap Changers (OLTCs), Distributed generation (DG), and Distributed static synchronous compensator (D-STATCOM) for power loss minimization and voltage deviation. In [18] a differential evolution (DE) is applied to solve the multi-objective optimal power flow considering the integration of Wind sources in coordination with STATCOM devices, and in [19], a probabilistic power flow strategy is proposed to solve single and multi objective based power loss and voltage deviation in the presence of photovoltaic distributed generators, in [20] a fully distributed reactive power optimization and control method for active distribution networks, in [21, 22], a distributed control algorithm is proposed for optimal reactive power control in power grids, in [23] three recent metaheuristic methods such as Grey Wolf, Dragonfly and Moth-Flame Algorithms have been successfully adapted and applied for optimal sizing and placement of capacitors in RD systems, in [24] a Flower Pollination Algorithm and Loss Sensitivity Factors is proposed to solve the optimal sizing and allocation of capacitors banks in RD systems, the main objective function considered is only the total power loss, in [25] a recent algorithm named Polar Bear Optimization Algorithm is successfully adapted and applied to solve the optimal allocation and sizing of conventional compensators based shunt capacitors in RD systems, the main objective function treated is the minimization of total power loss at normal exploitation, in [26]

the allocation problem of multi shunt compensators is solved using hybrid method based on analytical and two metaheuristic optimization techniques, in [27], a recent method named chaotic quasi oppositional chemical reaction optimization is applied to solve the reconfiguration of shunt compensators, in [28] a gravitational search algorithm is also applied to solve the allocation problem of shunt compensators, and in [29] an improved atom search optimization is used to solve size and allocation of multi distributed shunt compensators. Authors in [30] proposed a highly relevant technique to find the optimal location of a shunt compensator namely synchronous compensator (STATCOM) based FACTS technology to dampen the rotor angle oscillations and enhance the transient stability of multi machine systems.

Based on the statistical analysis of several optimization methods cited in the recent literature used to improve the performances of RD systems, it is found that the most of these methods are oriented to optimize the performances of RD systems at normal condition, second, various objective functions related to practical planning problems such as total power loss, the margin reserve, the reconfiguration process, allocation and sizing problems of shunt compensators are not treated in coordination. Optimal setting and sizing of multi-conventional compensators and shunt compensators based FACTS devices such as SVC and STATCOM, it is mandatory to consider critical operation of RD systems such as the critical load growth and severe faults.

In this paper a new optimization variant based tree-seed algorithm (TSA) recently proposed by *M. S. Kiran* [31] is adapted and applied to improve the performance of RD systems in terms of reduction of the total power loss, minimization of voltage deviation and improving margin reserve. To exploit efficiently the performances of radial distribution system in particular under critical load growth, a reactive power-planning strategy based STATCOM devices has been applied in coordination with the reconfiguration operation. It is found that reactive power control in the distribution system may be considered an important strategy to ensure service continuity and economic exploitation. The contributions of this paper are summarized as follows:

1. A novel variant based TSA is proposed to solve the reactive power dispatch and network reconfiguration in RD system.
2. In this study, the setting and sizing of multi STATCOM devices and multi PV sources are considered
3. The reactive power dispatch of multi STATCOM devices is optimized in coordination with multi PV sources at normal exploitation and considering critical load growth.

- Total power loss and margin reserve are two objective functions considered and optimized at normal condition and under load growth.

The paper is organized as follows: a brief review of the development and application of various metaheuristic methods in solving several problems related to power system planning and control is given in Sect. 1. Descriptions of RD and optimization formulation are introduced in Sect. 2. In Sect. 3, the basic principle of reactive power compensation is presented. Models of PV source and STATCOM devices are described in Sect. 4. The proposed TSA technique is detailed in Sect. 5, the obtained results are recapitulated and discussed in Sect. 6, and finally, useful conclusion and perspective work directions are given in Sect. 7.

2 Radial Distribution Eclectic Network

2.1 Overview

The well known the topology of the RD electric system has a simple structure and consists of one source named substation, one principal feeder and at least one derivation.

As well shown in Fig. 1, the voltage magnitude decreases toward end of the feeder, as the impedance of lines causes a voltage drop. Thus, for this simple topology, the weak bus with low voltage magnitude is located at the end of the feeder [1].

2.2 Basic power flow equations

2.2.1 Power loss in lines

The generalized formulas for active and reactive power loss in line located between bus k and bus $k+1$ are calculated using the following simplified equations [1]:

$$P_{loss}(k, k+1) = \left(\frac{P_{k,k+1}^2 + Q_{k,k+1}^2}{|U_k|^2} \right) R_{k,k+1} \quad (1)$$

$$Q_{loss}(k, k+1) = \left(\frac{P_{k,k+1}^2 + Q_{k,k+1}^2}{|U_k|^2} \right) X_{k,k+1} \quad (2)$$

2.2.2 Total power losses

The total real power loss of the RD electric system can be easily found by summing all the branches power loss and it is expressed as:

$$P_{t,loss} = \sum_{k=1}^{nbr} P_{loss}(k, k+1) \quad (3)$$

3 Optimization Tasks

The main objective of the proposed optimal planning strategy is to optimize the locations and sizes of multi-PV sources based renewable energy and multi-STATCOM devices to improve the performance of RD systems. The objective functions adopted in this study are the reduction

Fig. 1 Simple structure of radial distribution electric system

of active power losses and improving the margin reserve of the RD electric network while considering all security and operation constraints.

3.1 Objective functions

In this study, two objective functions are considered, the total power losses and the margin reserve of the RD electric network, these two objective functions are optimized considering all security constraints.

3.1.1 Minimization of total power loss

$$Obj1 = f_{loss} = \text{Min} \left(P_{t,loss} = \sum_{k=1}^{nbr} P_{loss}(k, k+1) \right) \quad (4)$$

3.1.2 Maximization of margin reserve (MR)

To ensure reliable exploitation and operation of modern RD in particular at critical situations such as load growth and faults, it is mandatory to reduce the reactive power transit in different branches. This objective function optimizes the reactive power flow in all branches to maximize the margin reserve of the principal transformer located at the substation and improving the MR of the large number of dispersed transformers (30/0.4 kV). The expression of this objective function is formulated as follows:

$$Obj2 = MR = \max \left(\frac{\text{real} \left(\sum_{k=1}^{NI} I_k \right)}{\text{imag} \left(\sum_{k=1}^{NI} I_k \right)} \right) \quad (5)$$

where, MR is the margin reserve, I_k is the current delivered to load at bus k , and NI is the number of load.

The lower reactive current delivered by the substation causes a higher margin reserve of the RD network. The reduced value of reactive current allows the substation to deliver supplementary active power to consumers with an admissible power quality in particular at critical situations such as faults and load growth.

3.2 Constraints

3.2.1 Equality constraints

The basic active and reactive power balancing constraint is expressed by the two following expressions:

$$P_{tr,slack} + \sum_{i=1}^{Npv} P_{pv,i} = \sum_{i=1}^{NI} P_{D,i} + \sum_{m=1}^{nbr} P_{loss,m} \quad (6)$$

$$Q_{tr,slack} + \sum_{i=1}^{Npv} Q_{pv,i} = \sum_{i=1}^{NI} Q_{D,i} + \sum_{m=1}^{nbr} Q_{loss,m} \quad (7)$$

3.2.2 Inequality constraints

The inequality constraints represent the security constraints related to the elements of the network distribution system.

3.2.3 Voltage constraint

The following expression represents the limits on voltage magnitudes at all buses

$$V_i^{\min} \leq V_i \leq V_i^{\max}, \quad i = 1, 2, \dots, Nbus \quad (8)$$

3.3 Renewable source constraints

The decision variables of various renewable sources (RS) used must be allowable in the range of size and power factor. For solar source the active power is restricted as follow:

$$P_{pv,i}^{\min} \leq P_{pv,i} \leq P_{pv,i}^{\max}, \quad i = 1, 2, \dots, Npv \quad (9)$$

- **Maximum level of RS penetration:**

The amount of active power to be injected in the network by RS is called the level of penetration of RS [1, 2]. In general, the constraint related to the penetration level is calculated as follows:

$$\sum_{i=1}^{Npv} P_{pv,i} \leq \mu \sum_{j=1}^{NI} P_{D,j} \quad (10)$$

where, μ is the penetration level.

- **STATCOM constraints:** the reactive power of STATCOM device integrated at bus i must be restricted within its admissible limit.

$$Q_{Stc,i}^{\min} \leq Q_{Stc,i} \leq Q_{Stc,i}^{\max} \quad (11)$$

- **Line current flow:**

All the currents transit in lines must be maintained below their admissible value.

$$I_{bri} \leq I_{bri}^{\max} \quad bri = 1, \dots, nbr \quad (12)$$

4 Principle of Reactive power compensation

The following steps explain the effect of reactive power compensation on voltage regulation and improvement of power factor using simplified linear mathematical equations. Figure 2 shows the basic principle of reactive power compensation.

1. *Before compensation:* The voltage drop between bus i and bus j before compensation is given as follow:

$$dU_{ij} = \frac{P_{ij} \cdot R_{ij} + Q_{ij} \cdot X_{ij}}{U_i} \quad (13)$$

2. *After compensation:* in order to improve the voltage magnitude at bus j , a specified value of reactive power is injected by the shunt compensator in bus j . The new expression of voltage drop magnitude is expressed as follows:

$$dU_{ij}^c = \frac{P_{ij} \cdot R_{ij} + Q_{ij}^c \cdot X_{ij}}{U_i} = \frac{P_{ij} \cdot R_{ij} + (Q_{ij} - Q_{Stc}) \cdot X_{ij}}{U_i} \quad (14)$$

$$dU_{ij}^c = \frac{P_{ij} \cdot R_{ij} + Q_{ij} \cdot X_{ij}}{U_i} - \frac{Q_{Stc} \cdot X_{ij}}{U_i} = dU_{ij} - dU_c \quad (15)$$

$$dU_c = \frac{Q_{Stc} \cdot X_{ij}}{U_i} \quad (16)$$

where, dU_c is the corrected voltage magnitude introduced by the compensator.

As well expressed in the expression (Eq. 16), the desired voltage magnitude to be controlled depends on the amount of reactive power to be exchanged with the electric network.

5 PV source and STATCOM controller modeling

5.1 PV source modeling

The PV source is an important type of renewable sources, largely used and integrated in many practical power systems. The PV can deliver only active power to the network. Like various renewable sources, the PV source has an intermittent aspect, which is considered as the major inconvenient of renewable sources. For this pertinent reason, the integration of PV source requires robust planning strategy based on active power dispatch in coordination with reactive power support. Figure 3 shows the basic model of PV source.

5.2 STATCOM controller modeling

STATCOM is one of the recent generation of the shunt FACTS devices commissioned and firstly installed in 1999 in a practical power system [19]. The STATCOM consists of voltage source converter build with Thyristors with turn-off capability, a coupling transformer, a DC capacitor, and controller unit [30]. The STATCOM device can generate or absorb reactive power to control the voltage at a specified bus. Firstly the main effect of STATCOM devices integrated

Fig. 2 Principle of shunt compensation: **(a)** Voltage regulation, **(b)** Power factor correction

Fig. 3 Simplified model of PV source

at specified location is to ensure fast reactive power control with the network [32]. Secondly, the STATCOM controller designed especially for shunt compensation has a better ability to deliver the maximum reactive power at critical situations such as severe contingencies and low voltage magnitudes. The reactive power control based STATCOM is more efficient than using SVC device and conventional compensators. The structure of STATCOM controller is shown in Fig. 4, the model of STATCOM is shown in Fig. 4a, and its steady state voltage-current characteristic is shown in Fig. 4b.

5.3 STATCOM modeling in power flow algorithm

An alternative way to model the STATCOM in the power flow algorithm is described in [19]. The generalized active

and reactive power equations related to STATCOM power flow model are formulated as follows:

$$P_{Stc} = V_k^2 \cdot g_{Stc} + V_k \cdot V_{Stc} (g_{Stc} \cdot \cos(\delta_{Stc} - \delta_k) + b_{Stc} \cdot \sin(\delta_{Stc} - \delta_k)) \quad (17)$$

$$Q_{Stc} = -V_k^2 \cdot b_{Stc} + V_k \cdot V_{Stc} (g_{Stc} \cdot \sin(\delta_{Stc} - \delta_k) - b_{Stc} \cdot \cos(\delta_{Stc} - \delta_k)) \quad (18)$$

where, V_k , is the voltage at bus k and V_{Stc} is the voltage delivered by STATCOM, $(\delta_{Stc} - \delta_k)$ is the difference angle between the two voltages, g_{Stc} , b_{Stc} are the conductance and the susceptance of the STATCOM respectively. Based on Fig. 4, c), it is found that the STATCOM has a robust characteristic compared to SVC device to deliver the maximum reactive power at low voltages. In this situation the STATCOM can operate in two modes:

- *Capacitive mode*: if $V_{Stc} > V_k$, the STATCOM operates in capacitive mode, and delivers reactive power to the network.
- *Inductive mode*: if $V_{Stc} < V_k$, the STATCOM operates in inductive mode, and absorbs reactive power from the network.

6 Optimization method based tree-seed algorithm

TSA is a novel optimizer introduced recently by M.S Kiran [31]. The proposed method is based on relation between trees and there seeds. The TSA is simple to program and to adapt and offers the ability to create flexible balance between the intensification and diversification during

Fig. 4 Structure of STATCOM: (a) Model of STATCOM, (b) Voltage-current characteristic of STATCOM

search process. The basic mechanism search of TSA is shown in Fig. 5.

- **Algorithm description**

It is well known, that in nature, trees spread to the surface through their seeds. Each tree has its associated seeds, these seeds grow over time and new generation of trees is formed to succeed the original trees. The interaction aspect between trees and their succeeded seeds may be relatively interpreted in mathematical form as follows:

- Firstly, the initial locations of trees are generated randomly and considered as a possible solution to the problem. Trees are assimilated to population term and associated to specified control variables. As well known, the traditional formula used to generate the initial population is given as:

$$T_{ij} = L_{j,\min} + r_{ij}(H_{j,\max} - L_{j,\min}) \quad (19)$$

where $L_{j,\min}$, $H_{j,\max}$ are the minimum and maximum values of decision variables respectively, r_{ij} is a random number in the range [0 1].

- The location of trees and seeds may be considered a candidate solution to an optimization problem. The possible location of various seeds produced from a tree is an important process. For this pertinent reason, the evolution of trees and seeds during the search process is exploited and generated using the following search equations:

$$S_{ij} = T_{ij} + \alpha_{ij} \times (B_j - T_{r,j}) \quad (20)$$

$$S_{ij} = T_{ij} + \alpha_{ij} \times (T_{i,j} - T_{r,j}) \quad (21)$$

where, S_{ij} is the j th dimension of i th seed designed to produce i th tree, $T_{i,j}$ is the j th dimension of i th tree,

Fig. 5 Basic mechanism search of TSA: (a) initial search space, (b) production of seeds, (c) new location of trees

B_j is the j th dimension of best tree location, T_{rj} is the j th dimension of r th tree randomly selected from the population. α is a scaling factor randomly generated in the range $[-1, 1]$.

The first equation (Eq. 20) considers the tree location that the seed will be produced for this tree and the best location of the tree population.

The second equation (Eq. 21) uses two different tree locations for producing a new seed for the tree.

During search process, one of the two equations (Eq. (20), Eq. (21)) may be selected to produce a new seed location. The selection is based on a control parameter named a search tendency (ST), the value of ST is randomly generated in the range $[0, 1]$, the higher value of ST provides an efficient local search; while small value of ST causes a powerful global search process.

- Finally, the best solution is obtained from the population, and using the following equation:

$$B = \min \left\{ f(\vec{T}_i), i = 1, 2, \dots, N_{tree} \right\} \quad (22)$$

where, N_{tree} is the population size, the detail steps of the original algorithm are given Fig. 6.

- Proposed planning strategy based TSA

Based on the flowchart shown in Fig. 7, the steps of the proposed planning strategy are summarized as follows:

1. Introduce all technical data of the RD electric network
2. Introduce the initial parameters of the TSA, in this study, the population is taken between 10 and 20 trees, ST equal 0.1, and the maximum number of generation is taken between 80 and 100, it depends on the size of the problem to be solved.
3. Run power flow to find the initial state of the network
4. Introduce the type of objective function to optimize, two objective functions have been considered, the minimization of total power loss and maximization of margin reserve security.
5. Find the best location of shunt compensators and PV sources based on sensitivity index.
6. Introduce the desired loading factor
7. At trail 1, run TSA, save the optimized results

Fig. 6 Stages of the standard TSA

Stage 1: Initialize the parameters of the TSA algorithm.

- Specify the number of population size (N_{pop}).
- Specify the value of ST parameter
- Specify the dimension of the problem (N_{vars})
- Specify the convergence criterion: maximum number of generation (G_{max}).
- Generate N random tree location using Eq. 19.
- Evaluate the tree location using the fitness function associated to the problem.
- Select the best solution using Eq. 22.

Stage 2: Begin search with Seeds

FOR all trees

Specify the number of seeds produced for this tree.

FOR all seeds

FOR all dimensions

IF (rand < ST)

Update this dimension using Eq. 20

ELSE

Update this dimension using Eq. 21

END IF

END FOR

END FOR

Select the best seed and compare it with the tree

If the seed location is better than tree location, the seed substitutes for this tree.

END FOR

Stage 3: Select the best solution of population.

If new best solution is better than the previous best solution, new best solution substitutes for the previous best solution.

Stage 4: Check the convergence criterion

If the criterion condition is not reached, go to Step 2.

Stage 5: Report the best solution

Fig. 7 Flowchart of the proposed planning strategy based TSA

8. For trail > 1: Execute intensification process: run TSA based on an updated population: $initial_population = best_pop_trail1$. After the first trail, the mechanism search will be oriented to execute intensification phase to well locate the near global solution and to escape from the local optimal solution.

8.1 The ST parameter is randomly adjusted to a high value to provide an efficient local search (intensification), the value of ST is adjusted to: $ST = ST (old) + rand/Itmax$

8.2 If the new best solution achieved is not improved, then the process search will be oriented to bascule again to the exploration stage, $ST = ST (old) - rand/Itmax$

8.3 Repeat all steps until the maximum number of trail is achieved

9. Save the final optimized results.

7 Cases analysis

Electric test system 1: Radial distribution system 33-buses.

This first test system consists of 32 lines and 33 buses, the RD 33-Bus has a voltage of 12.66 kV, the apparent power to satisfy at normal condition is $(3.715 + j 2.300)$ MVA.

Case 1: Optimal exploitation under normal condition considering one STATCOM device.

Scenario 1: The main objective of this first case is to optimize the total power losses by optimizing the reactive power of multi STATCOM exchanged with the network. Due to the economic aspect associated to STATCOM device, it is important to determine the size and number of STATCOM devices to be installed. For this pertinent reason, four STATCOM are used and located at buses (10, 18, 25, and 30), using sensitivity index [1, 2]. The initial sizes of STATCOM devices are taken in the range $[-1.5, 1.5]$ MVAR. First, the four STATCOM devices are integrated individually, as well depicted in Table 1, the best optimized power loss (0.1436 MW) is found by installing compensator at Bus 30, the critical value of voltage magnitude is 0.9131 p.u, the value of reactive power exchanged between the STATCOM and network is 1.2527 MVAR. Second, the four compensators are considered simultaneously. For this scenario, the total power loss is reduced to **0.131784** MW. The voltage magnitude is improved to **0.9407** p.u, the total reactive power of the four STATCOM devices optimized is **1.9009** MVAR. Figure 8 shows the convergence characteristics for power loss minimization based on one compensator at loading factor $KI = 1$.

Scenario 2: This scenario is investigated to optimize the total power loss and the total size of multi-STATCOM devices. For fair comparison with other techniques treating the same problem, only three STATCOM devices have been integrated in buses: 10, 18 and 30. By considering

the total size of compensators, the total power loss achieved is increased **135.0343** KW compared to the scenario 1, and the optimized total size of STATCOM devices is reduced from 1900.9 KVAR to **1543.70**, which is better and competitive compared to values found by all other techniques such as, Genetic Algorithm (GA), Plant Growth Simulation Algorithm (PSGA), Gravitational Search Algorithm (GSA), Simulated Annealing (SA), Interior Point (IP), Flower Pollination Algorithm (FPA), Moth Flame Optimization (MFO) Algorithm and grey wolf Optimization (GWO) Algorithm. The results obtained using the modified TSA, prove its flexible ability to locate with accuracy the near compromise optimal solution for power loss and the total size of multi distributed STATCOM compensators. The proposed technique may be suitable to solve various combined problems related to power system operation and control. Table 2 shows a comparative study between the proposed modified TSA and other recent techniques. The convergence behavior for power loss minimization considering the total size of multi distributed STATCOM devices is shown in Fig. 9.

Case 2: Optimal exploitation under load growth considering only one STATCOM device

The main task of this case is to determine the capability of one STATCOM device to improve the performance of RD system in terms of total power loss and minimum voltage magnitude. As well depicted in Table 3, at the loading factor 1.15, the best total power loss achieved is (**0.1961** MW) by installing one STATCOM at bus 30 which injects **1.1633** MVAR. The low voltage magnitude is **0.9109** p.u. The worst total power loss achieved is obtained by installing the STATCOM at bus 25.

Case 3: Optimal exploitation under load growth considering four STATCOM devices

In this case, four STATCOM devices have been investigated to optimize the total power loss at various loading factors (1.15, 1.3 and 1.4). As well depicted in Table 4, the four compensators allow RD system to

Table 1 Optimized RD performances under normal condition: integration one and four STATCOM devices

	STATCOM Location					
	Without STATCOM	10	18	25	30	10–18–25–30
PT (MW)	3.9177	3.8849	3.8975	3.9075	3.8586	3.8468
QT (MVAR)	2.4352	1.4820	1.9374	1.6993	1.1436	0.4871
PLoss (MW)	0.2027	0.1699	0.1825	0.1925	0.1436	0.131784
Vmin (p.u)	0.9131	0.9256	0.9213	0.9146	0.9256	0.9407
Vstc (p.u)	/	0.9524	0.9428	0.9788	0.9523	0.9519–0.9407–0.9779–0.9520
Size of STATCOM devices (MVAR)	/	0.9324	0.4860	0.7308	1.2527	0.3392, 0.1284, 0.4200, 1.0133
Total size of STATCOM devices		0.9324	0.4860	0.7308	1.2527	1.9009
Loss reduction (%)		16.18	9.97	5.03	29.16	34.73
Loading factor: KI	1	1	1	1	1	1

Bold format in tables indicate the best values achieved

Fig. 8 Convergence characteristics for power loss minimization based one compensator at loading factor $Kl=1$

maintain adequate power quality at high load growth. The total power loss achieved at high loading factor 1.4 is **0.2709** MW, the required reactive power of STATCOM devices installed at buses 10–18–25 and 30 are [0.5829–0.1805–0.6283–1.1961] respectively. Figure 10 shows the convergence characteristics for power loss minimization based four compensators at loading factors: 1–1.15, 1.3 and 1.4.

Case 4: Optimal exploitation under normal condition considering renewable PV sources and STATCOM devices:

In this case, two scenarios are treated. In the first scenario, four PV sources and four STATCOM devices are installed at buses 10–18–25–30. The limits of PV sources are in the range [0 1] MW. The initial sizes of all STATCOM devices are taken in the range [−1 1] MVAR. By considering the total power loss as the main objective function, the values of the optimized active power loss at various penetration level are (**0.0135**, **0.0172**, **0.0305**, **0.0535**, and **0.0870**) MW, respectively. As well depicted in Table 5, the total power loss is reduced at high level penetration (67.2947%). The voltage control of four STATCOM devices at a high level penetration is (0.9923, 1, 0.9862, and 0.9919). Figures 11 and 12, show the convergence characteristics of power loss minimization at all penetration level. Figure 13 shows the distribution of voltage magnitudes at all buses. As well shown in Figs. 11 and 12, the near optimal solution is obtained at a reduced number of iterations, less than 5 trials are necessary to locate the best solution. In the second scenario and for fair comparisons with other recent

techniques, the total power loss is optimized considering only the integration of four PV sources. As well shown in Table 6, the total power loss increased compared to the first scenario, this proves the importance of coordination between STATCOM devices and PV sources to reduce the total power loss. In order to validate the efficiency of the proposed TSA, results found have been compared to various recent optimization methods such as PSO, dynamic adaptation of PSO (DAPSO), Backtracking search optimization algorithm (BSOA), Improved analytical method (IA) and Multi objective PSO (MOPSO) [19]. Table 7 recapitulate a comparative study with other methods for power loss minimization at normal condition. The optimized active power loss achieved using the proposed TSA is **73.3** kW, this value obtained at penetration level **67.2947%**, which is better and competitive than that obtained using other methods, except the PSO (71.64 kW). However, it is important to note that the optimal power loss obtained by PSO [19] at high penetration level (78.73%), and at penetration level of 105.86% by using MOPSO [19]. Due to the intermittent and stochastic aspect of PV sources, the integration level of renewable sources must be limited within an admissible security value to ensure suitable margin stability and service continuity of the network.

Case 5: Optimal exploitation considering load growth based PV sources and STATCOM devices:

In this case, four PV sources and four STATCOM devices are installed and controlled to minimize the total power loss under load growth ($Kl=1.4$). The limits of PV sources

Table 2 Comparison results for power loss minimization of RD system 33 buses: three STATCOM devices

	Methods [24]									
	Without STATCOM	GA	PGSA	GSA	SA	IP	FPA	MFO	GWO	Proposed TSA
Year		2005	2011	2015	2015	2015	2016	2018	2018	2020
P _{Loss} (MW)	0.2027	135.5	135.4	134.5	151.75	171.78	134.47	134.0725	134.0725	135.0343
Loss reduction (%)	-	33.14	33.19	33.63	25.12	15.24	33.65	33.84	33.840	33.3821
V _{min} (p.u)	0.9131	0.9349	0.9463	0.9672	0.9591	0.9501	0.9365	0.940	0.940	0.9409
Optimal location and size of STATCOM devices (KVAR)	-	(8) 300 (15) 300 (20) 300 (21) 300 (24) 300 (26) 300 (28) 300 (27) 600	(6) 1200 (28) 760 (29) 200	(13) 450 (15) 800 (26) 350	(10) 450 (14) 900 (30) 350	(9) 450 (29) 800 (30) 900	(6) 250 (9) 400 (30) 950	(8) 450 (13) 300 (30) 900	(8) 450 (13) 300 (30) 900	(10) 370.00 (18) 128.40 (30) 1045.3
Total size of STATCOM devices (KVAR)	-	2700	2160	1600	1700	2150	1600	1650	1650	1543.70

Bold format in tables indicate the best values achieved

Fig. 9 Convergence characteristics for power loss minimization based three STATCOM devices at loading factor $KI = 1$ **Table 3** Optimized RD performances under loading conditions: integration one STATCOM

	STATCOM Location			
	10	18	25	30
PT (MW)	4.5016	4.5191	4.5330	4.4684
QT (MVAR)	1.7219	2.2530	1.9738	1.6127
P _{Loss} (MW)	0.2294	0.2469	0.2608	0.1961
V _{min} (p.u)	0.9135	0.9084	0.9005	0.9109
V _{stc} (p.u)	0.9447	0.9333	0.9755	0.9381
Size of STATCOM (MVar)	1.0776	0.5590	0.8474	1.1633
Loading factor: KI	1.15	1.15	1.15	1.15

Bold format in tables indicate the best values achieved

are in the range [0 1] MW, the initial size of all STATCOM devices are taken in the range $[-1.5 \ 1.5]$ MVAR. Table 8 depicts the optimized control variables for power loss minimization based on four PV sources and four shunt Compensators. The values of the optimized active power loss at various penetration levels are (**0.0267**, **0.0342**, **0.0606**, **0.1127**, and **0.1759**) MW respectively. The voltage control of four STATCOM devices at a high level penetration is (**0.9895**, **1.00**, **0.9810**, and **0.9890**). Figures 14, 15, show the convergence characteristics of power loss minimization at all penetration level. Figure 16 shows the distribution of voltage magnitudes at all buses. As well shown in Figs. 14, 15, the near optimal solution is obtained at a reduced number of iterations, less than 5 trials are required to locate the best solution.

Case 6: Maximization of margin reserve

The MR is an important index to test the efficiency and reliability of practical power system. MR is based

Table 4 Optimized RD performances under loading conditions: integration four STATCOM devices

	STATCOM Location		
	10–18–25–30	10–18–25–30	10–18–25–30
PT (MW)	4.4492	5.0591	5.4719
QT (MVAR)	0.5636	0.6625	0.8130
PLoss (MW)	0.1769	0.2296	0.2709
Vmin (p.u)	0.9313	0.9218	0.9154
Vstc (p.u)	0.9443,0.9313,0.9745,0.9444	0.9366,0.9218,0.9708,0.9368	0.9314,0.9154,0.9689,0.9268
Size of STATCOM (MVar)	0.3953,0.1478,0.4862,1.1700	0.4549,0.1674,0.5284,0.3301	0.5829,0.1805,0.6283,1.1961
Loading factor: KI	1.15	1.3	1.4

Bold format in tables indicate the best values achieved

Fig. 10 Convergence characteristics for power loss minimization based four compensators at loading factors: 1/1.5/1.3 and 1.4

on reducing the amount of reactive current flow at all branches which enhance the capability of transformers to deliver additional active power to new consumers. To show the main impact of this index, the system is optimized with and without PV sources and shunt FACTS devices. The optimized values of MR with and without STATCOM devices and PV sources at normal condition are shown in Table 9. At the base case ($KI = 1$), and without considering the PV sources and shunt FACTS devices, the margin reserve is 24.37%, however by considering both PV sources and the reactive power support of multi-STATCOM devices, the MR is increased to **85.34%** at penetration level of PV sources equal 53.8358%. This allows

the main transformer to deliver additional active power to new consumers without affecting the service quality.

7.1 Test system 2: RD network of the Sonelgaz company in Algeria

The departure of *M'lili* (30 kV) is powered from the Mobile station located in Oumeche; it supplies 213 substations HTA / BTA (30/0.4 kV), it consists of 235 lines and 236 buses. Based on 2017 statistical measures delivered by Sonelgaz Company, the maximum power demand to satisfy is $6.0591 + j4.5443$ MVA. The admissible currents in lines are 270 A for lines with conductor section of 93.3 mm² and 140 A for lines with Sect. 34.5 mm². Figure 17 shows one line schematic representations of departures

Table 5 Optimized control variables based four STATCOM devices and four PV sources: normal condition: $KI=1$

STATCOM Location	10-18-25-30	10-18-25-30	10-18-25-30	10-18-25-30	10-18-25-30
PT (MW)	1.2285	1.7322	2.2455	2.7685	3.3060
QT (MVAR)	0.4753	0.4721	0.4772	0.4814	0.6658
P_{pv10}	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv18}	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv25}	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv30}	1.0000	0.8000	0.6000	0.4000	0.2000
PLoss (MW)	0.0135	0.0172	0.0305	0.0535	0.0870
Vstc (p.u)	0.9923,1.0000 0.9862,0.9919	0.9914,0.9958 0.9913,0.9909	0.9818,0.9824 0.9880,0.9814	0.9720,0.9688 0.9847,0.9718	0.9620,0.9549 0.9813,0.9620
Size of STATCOM (Mvar)	0.3181,0.1190 0.4043,0.9937	0.3137,0.1294 0.4049,0.9919	0.3149,0.1281 0.4069,0.9932	0.3193 0.1275 0.4101 0.9970	0.4736 0.1275 0.4603 0.6332
Loading factor: KI	1	1	1	1	1
Penetration level %	67.2947	53.8358	40.3768	26.9179	13.4589

Bold format in tables indicate the best values achieved

Fig. 11 Convergence characteristics for power loss minimization based four PV sources (levels: 1–4) and four shunt compensators

associated with two sub stations located in Tolga and Oumeche (Sonelgaz Company). The one line electric network topology of *M'lili* departure is shown in Fig. 18. The departures of *M'lili* equipped with tie switches to be closed or opened in coordination with other departures at critical situations such as load growth or sever faults described as follows:

- Switch *J5193* with departure of *Oumeche*.
- Switch *J5436* with departure '*Ourelal*' from mobile station 220/30 kV located in Tolga region.
- Station 542 to Sect. 5436 from departure '*Ourellal*' mobile station 220/30 kV located in Tolga region.

It is important to clarify that, based on the technical data delivered by Sonelgaz Company, and due to economic constraints, the number of sectionalizing switches installed in the departure *M'lili* are not sufficient and their

Fig. 12 Convergence characteristics for power loss minimization based four PV sources (level 5) and four shunt compensators at loading factor $KI=1$

Fig. 13 Voltage profiles with PV sources integration levels and STATCOM devices: $KI=1$

actual location are not optimally chosen. In this study and due to the financial aspect, the proposed optimal reconfiguration strategy is adapted only to the existing operational switches. Also, and due to the incomplete data relative to

other departures such as *Ourelal* departure and *Oumeche* departure, only the existing operational sectionalizing switches are considered in the proposed reconfiguration strategy analysis.

7.2 Proposed reconfiguration strategy

For modern distribution system, several sectionalizing switches (SW_i) and various tie switches (TW_k) must be installed to improve the reliability of modern power system. Each departure is equipped with several sectionalizing switches and a specified number of tie switches to be operated with other departures. The steps of proposed reconfiguration strategy are summarized as follows:

Step 1: run power flow at normal and abnormal condition, to identify the technical state of each departure in terms of the weak and the best connection for each departure.

Step 2: create two initial global matrices, the first one contains, the available sectionalizing switches to be operated in each departure, and the second matrix contains, the available tie switches associated to each departure to be operated.

$$M_{sw}^{Dp} = \begin{bmatrix} SW_1^{Dp1} & SW_2^{Dp1} & \dots & SW_n^{Dp1} \\ \vdots & \vdots & \ddots & \vdots \\ SW_1^{Dpn} & SW_2^{Dpn} & \dots & SW_n^{Dpn} \end{bmatrix} \quad (23)$$

And at normal condition and initial situation, the matrix of sectionalizing switches of all departures is 'on', and is given as follows:

$$M_{sw}^{Dp}(N) = \begin{bmatrix} 1 & 1 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 1 \end{bmatrix} \quad (24)$$

Table 6 Comparison results for power loss minimization based PV sources integration: normal condition: $KI=1$

Methods [20]	Base case	DAPSO	IA	BSOA	PSO	MOPSO	Proposed TSA
PV location	/	10–18–31	6–12–31	13–28–31	14–24–30	3–14–31	10–18–25–30
PV (MW)	/	0.681 0.600 0.719	0.900 0.900 0.720	0.6320 0.4870 0.5500	0.7540 1.0994 1.0714	1.6762 0.9553 1.3013	0.5000 0.5000 1.0000
PLoss (kW)	202.67	92.55	81.05	89.05	71.64	87.30	73.7
Loading factor: KI	1	1	1	1	1	1	1
Total size of PV (MW)	/	2	2.52	1.6690	2.9248	3.9328	2.5
Penetration level (%)	0%	53.84%	67.86%	44.93%	78.73%	105.86%	67.2947
Vmin (p.u)	0.9131	0.9654	0.9690	0.9554	0.9687	0.9845	0.9675

Bold format in tables indicate the best values achieved

Table 7 Optimized control variables for power loss minimization based four PV sources: normal condition: $KI=1$

PT (MW)	1.2885	1.7934	2.3080	2.8331	3.3693
QT (MVAR)	2.3504	2.3527	2.3619	2.3783	2.4025
P_{pv10} (MW)	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv18} (MW)	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv25} (MW)	0.5000	0.4000	0.3000	0.2000	0.1000
P_{pv30} (MW)	1.0000	0.8000	0.6000	0.4000	0.2000
P Loss (kW)	73.5	78.383	93.000	118.050	154.317
Loading factor: KI	1	1	1	1	1
Total size of PV (MW)	2.5	2	1.5	1	0.5
Penetration level %	67.2947	53.8358	40.3768	26.9179	13.4589
Vmin (p.u)	0.9675	0.9579	0.9480	0.9378	0.9274

Bold format in tables indicate the best values achieved

The matrix of available tie switches is formulated as follows:

$$M_{TS}^{Dp} = \begin{bmatrix} TS_1^{Dp1} & TS_2^{Dp1} & \dots & TS_k^{Dp1} \\ \vdots & \vdots & \ddots & \vdots \\ TS_1^{Dpm} & TS_2^{Dpm} & \dots & TS_k^{Dpm} \end{bmatrix} \quad (25)$$

And at normal exploitation, the matrix of tie switches of all departures is given as follows:

$$M_{TS}^{Dp}(N) = \begin{bmatrix} 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \quad (26)$$

Step 3: for all selected departures, find the best SW (*best_SW*) to be operated to reduce total power loss without considering TW. Select the best switches.

Step 4: if the selected *best_SW* chosen are not enough, then, find the best TW (*best_TW*) associated to the best departure to transfer optimized active power considering the sectionalizing switches.

Step 5: if the *best_SW* associated and optimized tie switches (*best_TW*) associated to the first candidate departure are not enough, then the algorithm will search new additional TS (*New_best_TW*) associated to the second candidate departure.

Step 5: The program will terminate, if the desired objective is located, or the available candidate tie switches associated to all candidate departures are checked.

Stage 1: Power flow analysis at normal condition and considering load growth.

In this first stage, a preliminary analysis of the *M'lili* departure is achieved. The technical state of the network in terms of voltage profiles, total power losses and current transit in lines are obtained. For this stage, two scenarios are elaborated, in the first scenario, the system is studied at normal condition based on statistical measures elaborated in 2017, the value of total power loss is 0.2307 MW, and the low voltage (0.9490 p.u) is located at bus 152. In the second scenario, the system is studied at loading factor

Table 8 Optimized control variables based four STATCOM devices and four PV sources at high loading condition ($KI=1.4$)

STATCOM Location	10–18–25–30		10–18–25–30		10–18–25–30		10–18–25–30		10–18–25–30	
PT (MW)	1.7277		2.4352		3.1616		3.9137		4.6769	
QT (MVAR)	0.6699		0.6774		0.6734		0.8929		0.6888	
P_{pv10}	0.7000		0.5600		0.4200		0.2800		0.1400	
P_{pv18}	0.7000		0.5600		0.4200		0.2800		0.1400	
P_{pv25}	0.7000		0.5600		0.4200		0.2800		0.1400	
P_{pv30}	1.4000		1.1200		0.8400		0.5600		0.2800	
P Loss (MW)	0.0267		0.0342		0.0606		0.1127		0.1759	
Vmin (p.u)	0.9791		0.9797		0.9667		0.9445		0.9349	
Vstc (p.u)	0.9895	1.0000	0.9879	0.9940	0.9743	0.9752	0.9606	0.9560	0.9460	0.9359
	0.9810	0.9890	0.9878	0.9867	0.9831	0.9738	0.9786	0.9517	0.9736	0.9460
Size of STATCOM (MVAR)	0.4488	0.1614	0.4516	0.1825	0.4423	0.1800	0.6214	0.1787	0.4677	0.1788
	0.5664	1.3942	0.5710	1.3615	0.5715	1.3932	0.6311	0.9704	0.5868	1.4146
Loading factor: KI	1.4		1.4		1.4		1.4		1.4	
Penetration level %	67.2947		53.8358		40.3768		26.9179		13.4589	

Bold format in tables indicate the best values achieved

Fig. 14 Convergence characteristics for power loss minimization based four PV sources (levels: 1–4) and four shunt compensators at loading factor $Kl=1.4$

Fig. 15 Convergence characteristics for power loss minimization based four PV sources (level 5) and four shunt compensators at loading factor $Kl=1.4$

equal 1.7391. The minimum voltage magnitude 0.9079 p.u is also located at bus 152; the value of total power losses is incremented to 0.7497 MW. Figure 19 shows the distribution of voltage magnitudes at the normal case and considering load growth.

Stage 2: Reactive power planning at normal situation without reconfiguration strategy

To improve the performance of *M'lili* network at normal condition and considering load growth in terms of reduction of total power loss and improvement voltage

Fig. 16 Voltage profiles with PV sources integration levels and STATCOM devices: $Kl=1.4$

profiles, a reactive power planning strategy based STATCOM device is proposed. One and two STATCOM devices are investigated and installed at two candidate buses 152 and 53. By considering the integration of one STATCOM at bus 152, the optimized value of total power loss achieved is 0.20727 MW, the minimum voltage 0.9541 is located at bus 236; the optimized reactive power achieved is 1.1781 MVAR. The convergence characteristic for optimal power losses is shown in Fig. 20.

By installing one compensator at bus 53, the total power losses achieved is 0.1986 MW, the magnitude of minimum voltage is 0.9509 p.u located at bus 152, and the optimized reactive power delivered by the compensator

Table 9 Optimized MR with and without STATCOM devices PV sources at normal condition ($KI=1$)

	Without STATCOM & PV	With STATCOM and PV sources				
		Level 1	Level 2	Level 3	Level 4	Level 5
Penetration level	/	67.2947	53.8358	40.3768	26.9179	13.4589
Loading factor: KI	1	1	1	1	1	1
MR %	24.37	85.24	85.34	85.18	85.05	84.94

Bold format in tables indicate the best values achieved

Fig. 17 One line schematic representations of departures associated to two sub stations located in Tolga and Oumeche (Sonelgaz Company)

is 1.1681 MVAR. It is clear that the performances of the RD are improved by considering the installation of STATCOM device at bus 53. The convergence characteristic for total power losses minimization is shown in Fig. 21.

In the last scenario two compensators are considered simultaneously. The total power loss optimized to 0.1762 MW, the optimal value of reactive power of the two compensators installed at buses 53 and 152 are 1.0958 MVAR and 1.0695 MVAR respectively. The minimum voltage magnitude is 0.9624 p.u located at bus 231. It is important to note that the integration and coordination between two compensators improve the performance of the RD compared to case with only one compensator. Figure 22 shows the convergence characteristic of total power loss minimization considering two compensators.

Stage 2: Reactive power planning at load growth without consideration network reconfiguration

In order to achieve reliable decision about the number and the size of STATCOM devices to be installed in practical power systems it is required to optimize the performances of distribution power system under load growth. For this case, the reactive power planning is realised considering load growth. It is found that by installing one compensator at bus 152, the optimized value of total power loss achieved is 0.6583 MW, the minimum value of voltage is 0.9160 located at bus 236, and by installing one compensator at bus 53, the total power loss achieved is 0.6457 MW, the minimum value of voltage magnitude is 0.9111 p.u located at bus 152.

Fig. 18 One line electric network topology of *M'ili* departure with 236 buses

Fig. 19 Distribution of voltage magnitudes at normal condition and considering load growth

Figure 23 shows the convergence characteristics for power loss minimization under load growth ($KI = 1.7391$) based STATCOM devices. Table 10 shows the optimized results for reactive power planning at normal and under load growth.

Fig. 20 convergence characteristic for power loss reduction at normal condition based one STATCOM located at bus 152

Stage 3: Reactive power planning at normal and abnormal situations with consideration of reconfiguration operation

The reactive power planning is a vital technical action to be considered by experts to improve the performance of modern power system in terms of improving the voltage profiles and reduction of total power losses. However, reactive power planning considering technical and economical

Fig. 21 convergence characteristic for power loss reduction at normal condition based on one STATCOM located at bus **53**

Fig. 22 convergence characteristic for power loss reduction at normal condition based on two STATCOM located at buses **53** and **152**

aspect must be done in coordination with reconfiguration operation under critical situations. In this stage, the reactive power of STATCOM devices to be exchanged with the network are optimized considering the best locations of sectionalizing switches and tie switches installed by Sonelgaz Company at specified locations. It is found that sectionalizing switches and total number of tie switches proposed by Sonelgaz Company are not sufficient and their locations are not well chosen. For the economic aspect, only the available three tie switches are considered within the optimization process. At the margin stability, the loading factor is **1.7391**; the TSA is applied to find the best tie switches associated to all candidate departures and sectionalizing switches related to *M'lili* departure to be operated in coordination with reactive power of STATCOM devices. In the first stage, and based on the steps of reconfiguration strategy, the TSA identifies the optimal tie

Fig. 23 Convergence characteristic for power loss reduction under load growth ($K_l=1.7391$) without reconfiguration strategy: One STATCOM at Bus 53, 152, and two STATCOM at Buses 53–152

Table 10 Optimized results at normal and under load growth: reactive power planning

	STATCOM Location			
	Without STATCOM	53	152	53 and 152
Loading factor (K_l)	1.7391	1.7391	1.7391	1.7391
PLoss (MW)	0.7497	0.6457	0.6583	0.5662
Vmin (p.u)	0.9079	0.9111	0.9160	0.9319
Critical Bus	152	152	236	231
Q_STATCOM (MVAR)	0	1.4254	1.9923	1.9405/1.9969

switches to be operated, the best tie switches are located based on minimum power loss generated in *M'lili* departure, and this choice will not affect the energy quality delivered to other departures (*Ourelal* and *Oumeche*), the minimum voltage level is considered as an index of power quality. In the second stage, the TSA is applied to optimize the reactive power of STATCOM devices to be exchanged with the network. Table 11 shows the optimized results under load growth considering reconfiguration and reactive power planning. Figure 24 shows the convergence characteristic for the power loss reduction under load growth and considering reconfiguration strategy for one STATCOM device installed at bus 53, the total power loss achieved is 0.5337 MW, and by installing one STATCOM at bus 152, the total power loss achieved is 0.5765 MW, Fig. 25 shows the convergence characteristic for the power loss reduction under load growth with STATCOM device installed in bus 152. However, by installing two STATCOM,

Table 11 Optimized results under load growth considering reconfiguration and reactive power planning

	STATCOM Location			
	Without STATCOM	53	152	53 and 152
Loading factor (KI)	1.7391	1.7391	1.7391	1.7391
P _{Loss} (MW)	0.7497	0.5337	0.5756	0.4884
V _{min} (p.u)	0.9079	0.9285	0.9175	0.9323
Critical Bus	152	152	236	231
Q _{STATCOM} (MVAR)	0	1.9951	1.4942	1.7968/1.4569
N° of (SWi)/switched off	/	5	5	5
Proposed Internal tie switch (Departure of M'lili): TW_i	/	3	3	3
The best Tie Switch	/	<i>J5193 at Oumeche departure</i>		

Bold format in tables indicate the best values achieved

Fig. 24 Convergence characteristic for power loss reduction under load growth ($KI = 1.7391$) considering reconfiguration strategy: One STATCOM located at bus **53** **Fig. 25** Convergence characteristic for power loss reduction under load growth considering reconfiguration strategy ($KI = 1.7391$): One STATCOM located at bus **152** **Fig. 26** Convergence characteristic for power loss reduction under load growth ($KI = 1.7391$) considering reconfiguration strategy: Two STATCOM located at buses **53** and **152**

the optimized power loss is improved to **0.484** MW. The convergence characteristic for power loss reduction under load growth and with two STATCOM devices installed in bus 53 and Bus 152 is shown in Fig. 26.

7.3 Overall comments and recommendations

- To achieve service continuity on all radial distribution systems of Sonelgaz Company (30/0.4 kV) with high power quality in particular at critical situations such as faults and load growth, it is absolutely recommended to install more internal tie switch within each departure. However, this important technical task causes supplementary cost.
- To ensure reliable exploitation of RD electric system in particular in summer period characterized by low voltage and important power loss, it is mandatory to coordinate the reconfiguration strategy with reactive power planning.

- It is recommended developing interactive energy management software to ensure real-time exploitation of distribution system at low cost investment.
- The optimal location of multi-shunt compensators based FACTS devices and the optimal selection of various sectionalizing and tie switches is a vital task to experts. This operation requires introducing the investment cost of all equipment.
- It is demonstrated that the integration of renewable sources in particular PV sources in coordination with shunt compensator (STATCOM) gives the highest power loss reduction and low voltage deviation at normal condition and at critical loading margin stability.
- For case 4, and by executing the program on a computer with processor i3, the average computation time required to achieve the best solution using the standard TSA is 7.7824 s, however, by using the proposed adaptive TSA, the average computation time required to locate the best solution is 2.36258 s, which is lower and competitive compared to the value obtained using the standard TSA. Our future work will be focused to apply the proposed variant based TSA for real-time application by using parallel processors in solving multi-objective problems related to large-scale reactive power system planning and control.

8 Conclusion

This study focuses on the improvement of the technical performance of radial electric distribution system by optimal location and sizing of STATCOM devices and multi-PV sources in coordination with optimizing a certain number of sectionalizing switches and tie switches to be operated. A recent metaheuristic technique called tree seed algorithm is efficiently adapted and applied to minimize the total power losses under normal condition and considering critical load growth. Two practical electric test systems are considered (standard 33 buses and 250 buses of Sonelgaz distribution systems of Algeria) to validate the efficacy and particularity of the proposed planning strategy. It is well demonstrated that the reactive power planning based STATCOM devices in coordination with active power management of multi PV sources will be considered an alternative solution to improve the power quality delivered to customers. However, at important load growth and severe critical faults, the desired power quality delivered to consumers will be affected, which requires the application of a flexible planning strategy based reconfiguration of network topology to achieve high technical and economical objectives. Due to the remarkable results found using the proposed planning strategy based TSA, author

will strive to apply an extended version of this algorithm to solve the distribution power system planning considering various dynamic characteristics of loads and taking in consideration the probabilistic and intermittent aspect of photovoltaic and wind sources. Otherwise, by using the parallel concept, the modified TSA may be useful for real-time applications in solving multi-objective power system planning and control for large-scale RD systems.

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Compliance with ethical standards

Conflict of interest No potential conflict of interest was reported by the author.

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