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OPTIMAL POWER MANAGEMENT OF DGS AND DSTATCOM USING IMPROVED ALI BABA AND THE FORTY THIEVES OPTIMIZER

Belkacem Mahdad

Department of Electrical Engineering, University of Biskra, Algeria

Abstract. *In this study an improved Ali Baba and the forty thieves Optimizer (IAFT) is proposed and successfully adapted and applied to enhance the technical performances of radial distribution network (RDN). The standard AFT governed by two sensible parameters to balance the exploration and the exploitation stages. In the proposed variant a modification is introduced using sine and cosine functions to create flexible balance between Intensification and diversification during search process. The proposed variant namely IAFT applied to solve various single and combined objective functions such as the improvement of total power losses (TPL), the minimization of total voltage deviation and the maximization of the loading capacity (LC) under fixed load and considering the random aspect of loads. The exchange of active powers is elaborated by integration of multi distribution generation based photovoltaic systems (PV), otherwise the optimal management of reactive power is achieved by the installation of multi DSTATCOM. The efficiency and robustness of the proposed variant validated on two RDN, the 33-Bus and the 69-Bus. The qualities of objective functions achieved and the statistical analysis elaborated compared to results achieved using several recent metaheuristic methods demonstrate the competitive aspect of the proposed IAFT in solving with accuracy various practical problems related to optimal power management of RDN.*

Key words: *Ali Baba and the forty thieves Optimizer, Integration of distributed generation, RDN, DSTATCOM, Power losses, loading capacity*

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Corresponding author: Mahdad Belkacem
Department of Electrical Engineering, University of Biskra, Al
E-mail: belkacem.mahdad@univ-biskra.dz

LIST OF ABBREVIATIONS

IAFT	Improved Ali Baba and the Forty Thieves
RDN	Radial Distribution Network
TPL	Total Power Losses
TVD	Total Voltage Deviation
LC	Loading Capacity
PV	Photovoltaic Systems
DSTATCOM	Distributed Static Compensator
SC	Shunt Compensator
DG	Distributed Generation
FACTS	Flexible AC Transmission Systems
CB	Capacitors Bank
GWO	Grey Wolf Optmizer
ABC	Artificial Bee Colony
ACA	Ant Colony Algorithm
IWHO	Improved Wild Horse Optimization Algorithm
SD	Standard Deviation
BSOA	Backtracking Search Optimization Algorithm
SIMBO-Q	Swine Influenza Model-Based Optimization with Quarantine
HHO	Harris Hawks Optimization Algorithms
MOIHHO	Multi-Objective Improved Harris Hawks Optimization Algorithms
IEO	Improved Equilibrium Optimizer
PM	Power Management
LMS	Loading Margin Stability
FWA	Fireworks Algorithm
BFOA	Bacterial Foraging Optmization Algorithm
HSA	Harmony Search Algorithm
TM	Taguchi Method
GA/PSO	Genetic Algorithm/Particle Swarm Optimization
WCA	Water Cycle Algorithm
TSA	Tabu Search Algorithm
ITSA	Improved Tabu Search Algorithm
EGWA	Enhanced Grey Wolf Algorithm
MRFA	Manta Ray Foraging Algorithm
JFSA	Jellyfish Search Algorithm
MC	Margin Capacity
RDN	Radial Distribution Network
TLBO	Teaching-Learning Based Optimization
QOSIMBO-Q	Quasi-Oppositional Swine Influenza Model-Based Optimization with Quarantine
IHHO	Improved Harris Hawks Optimization Algorithms
FUZZY-IAS	Fuzzy And Artificial Immune System

1. INTRODUCTION

Due to economic aspect, the radial distribution network (RDN) is exploited based on simple topology, as a result the energy quality delivered to consumers is greatly affected which requires urgent measures and additional costs to satisfy the desired objectives. Actually, with the large diffusion of various types of renewable sources such as wind and photovoltaic (PV) energy, the RDN becomes more flexible to exploit in terms of improving the energy quality, reducing cost investment and emission. Otherwise, the intermittent aspect of this energy is the main drawback which affects the energy quality delivered to consumers. Recently, many smart management strategies based on the adaptation of several novel metaheuristics methods have been proposed for integration of various types of renewable sources to improve the performances of modern RDN [1].The various power management strategies developed until now aim to find the optimal solutions to the following technical and economic problems, such as: what are the best locations and size of multi types of DGs units, how to find the best locations of conventional capacitor banc (CB) and shunt compensators (SC) based FACTS devices [1], how to optimally coordinate the amount of active powers of various types of DGs units and the reactive powers of shunt compensators [2], to optimize individually and simultaneously several objective functions, and finally how to design the optimal reconfigurations of RDN under normal and abnormal situations in the presence of multi DGs and SC to reduce the total power loss (TPL), improve the total voltage deviation (TVD), reduce emission, and enhance the total cost investment of modern RDN. A deep statistical review of large number of metaheuristic methods introduced in the recent literature reveals that the success of the majority these methods depends on the structure of the diversification and intensification mechanism. Dynamic interactivity between exploration and exploitation during search process allows the algorithm to solve with accuracy various complex optimization problems [1, 2]. Among many developed strategies based recent metaheuristic methods applied with success to improve the technical and economical performances of RDN, authors in [3] proposed a hybrid technique based on combining an analytical method and metaheuristic optimization techniques for solving the optimal location of bank capacitors to improve the performances the various RDN. In [4] a water cycle algorithm is adapted and applied to solve the location and sizing of bank capacitors and DGs in RDN. In [5] an efficient Jellyfish Search Algorithm is successfully applied to solve the power management of RDN such as the location and coordination of shunt compensators based FACTS devices and DGs, and the reconfiguration operation to improve the power quality delivered to consumers such as the improvement of voltage deviation and the reduction of the TPL. In [6], three novel metaheuristic methods such as the Grey Wolf optimizer, the Dragonfly and Moth–Flame Optimization Algorithms have been applied to solve the optimal location and sizing of multi DGs and CB in RDN. In [7], a spring search algorithm is applied to solve the optimal integration of capacitor banks and various DGs; various objective functions have been treated to elevate the RDN performances. In [8] a hybrid method based on combining the GA and the PSO algorithm for optimal setting and sizing of multi DGs units, the various multi objective problems are transformed to a single objective function by employing fuzzy optimal theory. In [9], a combined technique based on Genetic Algorithm and Mathematical Optimization, is presented to improve the operating cost and reducing the TPL, the particularity of the proposed hybrid method validated on three test RDN (10-Bus, 33-Bus and 69-Bus). In [10] artificial bee colony (ABC) method is investigated for optimal location of DGs considering the operation cost and TPL in RDN. In [11] a probabilistic technique based PSO is proposed for optimal allocation of DSTATCOM based FACTS devices in coordination with renewable sources such as wind turbines and solar photovoltaic (PV) to enhance the RDN. In [12] an approach based on ant colony algorithm (ACA) for optimal location of DGs to reduce TPL and improve the voltage profile of loads. In [13] a novel quasi-oppositional chaotic Harris hawk's optimization (QOCHHO) algorithm is adapted to solve the optimal sitting and sizing of distributed generation (DG) installed in the 33-Bus and the practical Brazil 136-bus radial distribution network (RDN) considering different types of load models at three load levels). In [14], an Improved Wild Horse

Optimization algorithm (IWHO) is proposed to improve the reliability of various RDN test systems, the 33-Bus, 69-Bus and the 119-Bus. In [15] a new circuit theory based branch oriented for loss allocation in RDN considering different load model and DGs units. In [16], an improved equilibrium optimizer (IEO) designed for selecting the suitable location and the most effective size of DGs based PV systems in practical RDN. Due to the robust characteristic and fast response of the STATCOM device to regulate the voltage magnitude in particular at critical situations such as severe faults, this device is also investigated by researches to improve the system loadability of multi machine based on Imperialist competitive algorithm [17] and Cuckoo Search algorithm [18]. In [19] ant lion algorithm is applied for optimal allocation and sizing of various DGs based renewable sources. In [20], an efficient reactive power management strategy based on a modern metaheuristic algorithm is proposed for reduction the TPL in RDN. In [21], a new optimization variant namely a novel opposition-based tuned-chaotic differential evolution technique designed to improve the techno-economic aspect of the optimal placement of DGs in RDN. In [22], an enhanced equilibrium optimizer (EEO) is applied for optimal planning of PV-BES units in RDN considering time-varying demand. In [23], a parallel slime mould algorithm (PSMA) is proposed for optimal reconfiguration of RDN in coordination with DGs integration. In [24], a hybrid genetic dragonfly algorithm (HGADA) is proposed and applied for optimal allocation of DGs to improve the technical performances of RDN. In [25], a planning strategy based on an improved grey wolf optimizer (IGWO) and loss sensitivity (LS) is proposed to improve the integration of DGs in RDN. In [26] an improved coyote optimization algorithm (ICOA) is proposed for optimally installing solar Photovoltaic sources in RDN. In [27], a single and multi objective technique based on an Improved Harris Hawks Optimizer (IHHO) is applied for optimal location and sizing of multi DGs. In [28], an improved meta-heuristic method is proposed to maximize the penetration level of multi DGs in RDN. In [29], a novel hybrid technique is proposed to solve the multi objective problem related to the integration of multi CBs and multi DGs in RDN.

Recently, authors in [30] developed a novel optimizer tool namely Ali Baba and The Forty Thieves (AFT). The efficiency of this technique validated on many modal and multi benchmark functions [30].Results confirmed the particularity of this technique and its ability to solve complex optimization problems. The best of our knowledge there is no application of this technique to solve practical problems related to power system operation and control, otherwise, it is found that the two proposed critical values of the standard algorithm which are responsible to create balance between exploration and exploitation are not generalized and depends on the problem to be solved. The main contributions of this paper compared to existing in the literature are summarized as follows:

1. A novel variant based AFT is proposed and successfully applied to solve the power management of practical RDN.
2. The modification introduced in the standard AFT algorithm allows the mechanism search to be more flexible and interactive to locate the global solution.
3. The active power of multi DGs units and the reactive power of multi DSTATCOM devices are optimized in coordination to improve the performance of two standard RDN, the 33-Bus, and the 69-Bus.
4. Obtained results are compared to many recent metaheuristic methods demonstrate the efficiency of the proposed IAFT in solving optimal power management of various RDN.

2. FORMULATION OF THE ENERGY MANAGEMENT PROBLEM

The strategy of power management (PM) consists in improving the performances of modern RDN by optimizing individually or simultaneously several objective functions formulated as follows:

2.1. TPL improvement

The objective function associated to minimization of TPL is expressed as follow:

$$Obj\_1 = TPL = Min\left(\sum_{k=1}^{nbr} P_{loss}(k,k+1)\right) \tag{1}$$

where, the active and reactive power losses in lines are expressed by the following expressions:

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

$$Q_{loss}(k,k+1) = \left(\frac{P_{k,k+1}^2 + Q_{k,k+1}^2}{|U_k|^2}\right) \times X_{k,k+1} \tag{3}$$

2.2. Improvement of Loading Capacity

Margin capacity (MC) known also as loading margin stability (LMS) of RDN reflects the capability of the RD network to deliver energy quality under sever situations such as faults and load growth. Delivering power quality to consumers under this critical situation is a challenge for expert. In such situation, it is mandatory to dispatch optimally the reactive power delivered by the substation and the reactive power to be injected or absorbed by the distributed STATCOM devices. The lower reactive power delivered by the principal transformer, improves the MC of the RDN. The objective function related to the MC is expressed as follows:

$$Obj\_2 = \max\ (MC) \tag{4}$$

where, MC is the margin capacity of the RDN.

2.3. Minimization of TVD

The mathematical expression associated to the minimization of the normalized TVD is formulated as follow:

$$Obj\_3 = \min\ (TVD) = \min\left(V_{des} - \sum_{i=1}^{Npq} (V_i)\right) \tag{5}$$

where; V_{des} is the permissible voltage magnitude, V_i is the voltage magnitude reported at load buses, Npq is the number of load buses.

2.4. Improvement the TVD and the TPL

The TPL and the TVD may be two conflict objective functions. For practical planning and operation of RDN, it is mandatory to find the equilibrium balance between TPL and TVD to ensure efficient power quality. This multi objective problem may be solved using the following mathematical expression:

$$Obj\_4 = \min\ (TVD, TPL) = \min\ (\alpha \times TPL + (1-\alpha) \times TVD) \tag{6}$$

where, α, is a balancing coefficient introduced to find the compromise solution between TPL and TVD. The two weighting coefficients are selected in the range [0 1].

2.5. Operation constraints management

2.5.1. Active and reactive power balance

To ensure reliable operation of RDN under normal and abnormal conditions, it is mandatory to ensure the following equality constraints:

$$P_{Tr,slack} + \sum_{i=1}^{ndg} P_{DG,i} = \sum_{i=1}^{Nl} P_{D,i} + \sum_{k=1}^{nbr} P_{loss,k} \tag{7}$$

$$Q_{Tr,slack} + \sum_{i=1}^{ndg} Q_{DG,i} = \sum_{i=1}^{Nl} Q_{D,i} + \sum_{k=1}^{nbr} Q_{loss,k} \tag{8}$$

2.5.2. Security constraints

The security constraints consist of inequality constraints associated to the secure operation of all elements of the RDN.

- Voltage constraint:

The voltage magnitude is an important index of power quality. To satisfy consumers the voltage magnitude must be within security values.

$$V_i^{\min} \le V_i \le V_i^{\max},\ i = 1,2,\ldots,Nbus \tag{9}$$

- *DG constraints*

The active power delivered by the DG units which considered as a control variable must be controlled within specified security limits.

$$P_{DG,i}^{\min} \le P_{DG,i} \le P_{DG,i}^{\max},\ i = 1,2,\ldots,ndg \tag{10}$$

- *Level of DG integration*

Due to the stochastic and intermittent aspect of various types of DGs, the exchanged of active powers delivered by various DGs such as PV and Wind sources must be dispatched within their security range. The penetration level (μ) to satisfy is introduced within the following operation inequality constraint:

$$\sum_{i=1}^{ndg} P_{DG,i} \le \mu \sum_{j=1}^{Nl} P_{D,j} \tag{11}$$

where, μ is the level of active power penetration in the RDN.

- *DSTATCOM constraints*

  The DSTATCOM device must be operated within its admissible reactive power limits.

$$Q_{Stc,i}^{\min} \leq Q_{Stc,i} \leq Q_{Stc,i}^{\max} \tag{12}$$

- *Line current transit in branches:*

  The transit of currents in lines must be controlled without violation their permissible value.

$$I_{li} \leq I_{li}^{\max} \quad i = 1.....nl \tag{13}$$

3. Modeling of DSTATCOM Device

The DSTATCOM device is a shunt compensator from the FACTS family designed principally to regulate the voltage magnitude at specified bus.

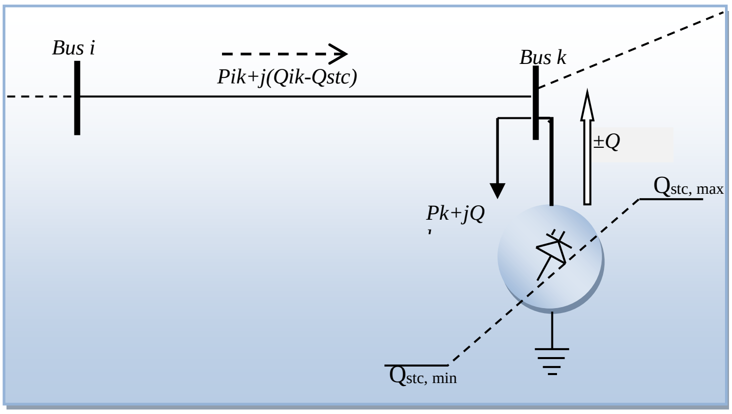

Fig. 1 Model of DSTATCOM device

Compared to the capacitor bank (CB) and to the SVC devices the DSTATCOM controller consists of a robust characteristic capable to regulate the voltage magnitude at critical situations. The DSTATCOM devices can regulate the voltages by injecting or absorbing reactive power from the network. Fig. 1 shows the basic structure of the DSTATCOM device.

3. Distributed Generation

For practical installation, as well shown in Fig 2, the DGs units are classified on three categories:

Category 1: This category include al types of DGs units which can only exchange the active power with the network such as the PV sources which have been intensively integrated in many practical electrical networks in world.

Category 2: This category includes DGs units which can exchange the active power with the network and absorb the reactive power. The wind sources based renewable sources are also integrated in various electrical networks.

Category 3: This category include al the DGs units which can exchange the active power with the network and absorb or inject the reactive power. These DGs are efficient which allows to control simultaneously the active power and the reactive powers with the network.

In this study an alternative solution is proposed to relieve the main drawback of the PV sources by installing shunt compensator based FACTS devices such as the DSTATCOM to ensure flexible control of reactive power in coordination of the active powers.

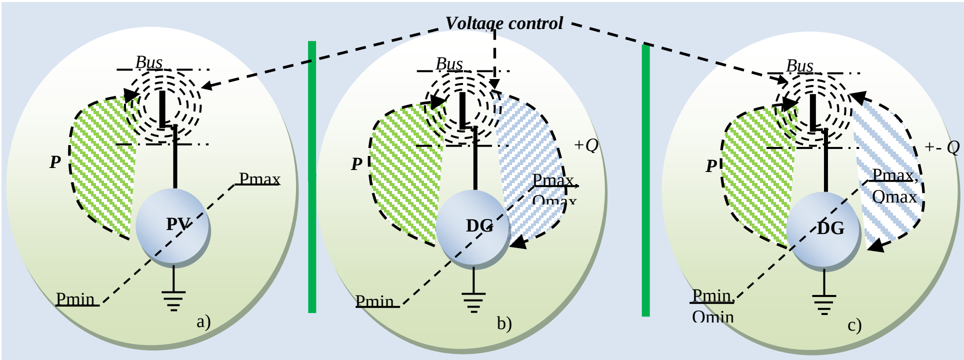

Fig. 2 Categories of DGs units: a) DGs with only active power control, b) DGs with active power control and only reactive power absorption, c) DGs with active and total reactive power control

4. Ali Baba and the Forty Thieves Optimizer

The AFT mimics the human intelligence and interactivities to find the best food's sources, materials and treasures. The current algorithm is particularly inspired from the famous tale of Ali Baba and the Forty Thieves. The following key words summarize the main strategy of the proposed AFT [30]:

- In the tale of Ali Baba, the thieves' behavior tries to find the location of Ali Baba, so the thieves are the individuals in the search space (environment).
- The home of Ali Baba is the objective function to achieve
- Ali Baba location is considered as the global solution
- The forty thieves search within an interactive group, they travel from an initial location and try to find the best location which is the house of Ali Baba.
- Marjaneh is considered as an intelligent operator designed to deliver astute ways to protect Ali Baba.

4.1. Modeling of AFT optimizer

- Initial positions of n individuals are generated randomly in the search space characterized by d dimension.

$$X = \begin{bmatrix} X_1^1 & X_2^1 & . & . & X_d^1 \\ X_1^2 & X_2^2 & . & . & X_d^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ X_1^n & X_2^n & . & . & X_d^n \end{bmatrix} \tag{14}$$

X_j^i denotes the *jth* dimension of the *ith* thief (individual),

$$X^i = LB_j + rand(UB_j - LB_j) \tag{15}$$

X^i, is the position of the *ith* individual in the search space, UB_j, LB_j denotes the upper and lower bunds in the *jth* dimension,

- Initialize randomly the wit level of Marjaneh as follow:

$$m = \begin{bmatrix} m_1^1 & m_2^1 & . & . & m_d^1 \\ m_1^2 & m_2^2 & . & . & m_d^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ m_1^n & m_2^n & . & . & m_d^n \end{bmatrix} \tag{16}$$

Fitness evaluation: the values of control variables are evaluated during search process based on each thief's position using the following matrix form.

$$f = \begin{bmatrix} f_1([\,X_1^1 & X_2^1 & . & . & X_d^1\,]) \\ f_2([\,X_1^2 & X_2^2 & . & . & X_d^2\,]) \\ . & . & . & . & . \\ . & . & . & . & . \\ f_n([\,X_1^n & X_2^n & . & . & X_d^n\,]) \end{bmatrix} \tag{17}$$

Update locations of thieves: the new locations of thieves can be updated using the following expression:

$$\begin{aligned} &X_{it+1}^i = gbest_{it} + \left[Td_{it}(best_{it}^i - y_{it}^i)\, r_1 + Td_{it}(y_{it}^i - m_{it}^{a(i)})\, r_2\right] \operatorname{sgn}(rand - 0.5) \\ &r_3 \geq 0.5, \quad r_4 > Pp_{it} \end{aligned} \tag{18}$$

Where; X_{it+1}^i denotes the position of the *ith* thieve at iteration (*it*+1), y_{it}^i is the position of the Ali Baba at iteration it, Td_{it} is the tracking distance of the thieves at iteration it, Pp_{it} is the perception potential of the thieves at iteration it, and $m_{it}^{a(i)}$ denotes the Marjaneh's intelligence level, the parameter a is defined as:

$$a = [(n-1)\, rand\, (n-1)] \tag{19}$$

The tracking distance and the perception potential are formulated as follow:

$$Td_{it} = \alpha_0 e^{-\alpha_1 \left(it/_{it\max} \right)} \tag{20}$$

$$Pp_{it} = B_0 \log\left(it/_{it\max} \right)^{B_0} \tag*{21)}$$

Update Marjaneh astute plane using the following expressions:

$$m_{it}^{\alpha(i)} = \begin{cases} X_{it}^{i} & if \;\; f(X_{it}^{i}) \geq f(m_{it}^{\alpha(i)}) \\ m_{it}^{\alpha(i)} & if \;\; f(X_{it}^{i}) < f(m_{it}^{\alpha(i)}) \end{cases} \tag{22}$$

where, $f\,(.)$ denotes score of the fitness function.

The key steps of the standard AFT algorithm [30]
Input setting variables of AFT: Pop_size, Iter_max, Trial_max, Dim, ubj, lbj
Randomly generate initial position, x, of all individuals (thieves) in the search space
Initialize the best position ($best^{i}_{it}$) and the global best position ($gest^{i}_{it}$)for all individuals
Initialize the intelligence degree of Marjaneh with respect to all individuals
Evaluate the position of all individuals using the appropriate fitness function ($f(x)$)
Set $it \leftarrow 1$
while ($it < it$_max) do
calculate Td_{it} using Eq.20
calculate Pp_{it} using Eq.21
for $i = 1,2,...,n$ *do*
if (rand ≥ 0.5*) then*
if (rand $\geq Pp_{it}$*) then*
update x^{i}_{it+1} using Eq. 18
else update x^{i}_{it+1} using Eq.15
end if
else
update x^{i}_{it+1} using Eq.18
end if
end for
for $i = 1,2,...,n$ do
Check the feasibility of the new position
Evaluate and update the new position of the individuals (thieves)
Update the solution $best^{i}_{it}$ and $gest^{i}_{it}$
Update m^{α}_{it} using Eq. 22
end for
$it=it+1$
end while

4.2. Proposed variant

The main contribution of this proposed variant is related to its ability to ensure the interactivity between the exploration phase and the exploitation phase during search process. The following are the modifications introduced to improve the performances of the original algorithm:

The first modification: The standard AFT is governed by various parameters to be well carefully identified and adjusted to achieve the near global solution. Among these parameters, the tracking distance (Td) and the perception potential (Pp).The following proposed modeling expressions are suggested to create flexible balance between diversification and intensification. Fig. 3 shows the evolution of the proposed Tracking distance (Td) and Perception potential (Pp) during search process.

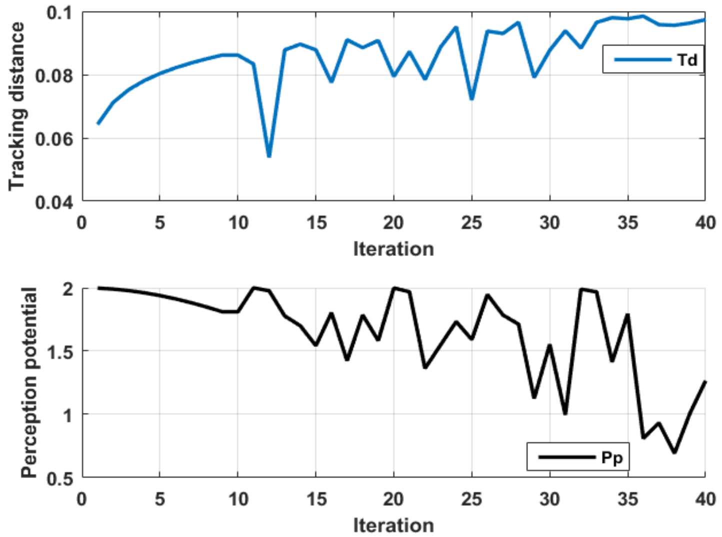

Fig. 3 Evolution of the proposed Tracking distance (Td) and Perception potential (Pp) during search process

4.3. Analysis methodology

The following steps summarize the analysis methodology based IAFT designed to solve various single and multi objective functions:

1. Read the technical data of the RDN such as the line data, load data,
2. Select and specify the objective function
3. Introduce the initial parameters of the IAFT, such as: population size, generation max, trials.
4. Run power flow tool to determine the initial state of the RDN in terms of total power loss, low voltage magnitude, maximum current transit in lines.
5. Select preliminary buses to install DGs and DSTATCOM devices based on sensitivity power index.
6. Run IAFT to minimize the objective function
7. Save the best solution
8. Check the convergence condition based on G_{max} and T_{max}
9. Return the optimized solutions such as the best active of DGs, the reactive power of DSTATCOM, and the voltage profiles.

5. STATISTICAL RESULTS ANALYSIS

5.1. Test 1: RDN 33-Bus

This first RDN 33-Bus consists of 32 lines and 33 buses; the active and reactive power of loads to satisfy is 3.715 MW and 2.300 MVAR respectively [2, 31]. Fig 4 shows the standard topology of the RDN 33-bus. The performances of the proposed optimizer tool namely IAFT is demonstrated via experiencing the following test cases.

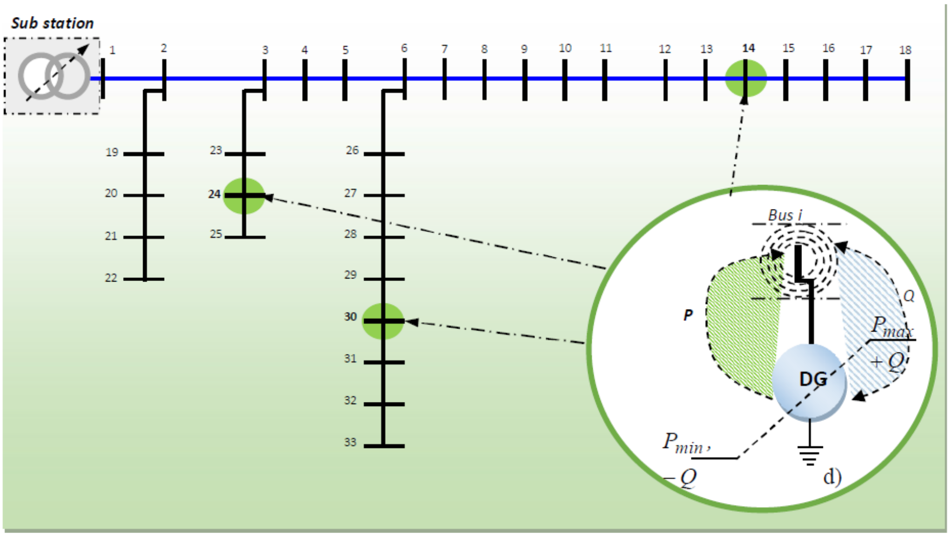

Fig. 4 The topology of the RDN 33-Bus

5.1.1. Case 1: TPL improvement based DSTATCOM under normal condition

This test case is focused to show the impact of integration only three STATCOM devices on the performances of RDN with 33-Bus. Three efficient locations are considered in buses 14, 24 and30. The maximum size of each STATCOM device is 1 MVAR. By considering the voltage limits of all PQ buses in the range [0.95 1.05] p.u, the optimized TPL found using the proposed IAFT is 126.5868 KW and by considering voltage limits in the range [0.9 1] p.u, the optimal TPL achieved is 132.2102 KW. Detailed optimized results related to decision variables of this case are shown in Table 1.The results of this case are compared to various metaheuristic methods such as: PSGA, GSA, SA, IP, FPA, MFO, GWO, DFO, PSO, and water cycle algorithm (WSA), it is absolutely clear that the proposed IAFT achieves better solution quality. The lowest voltage magnitude is 0.95 p.u reported at Bus 18. The convergence behaviour of TPL is shown in Fig. 5, it is important to mention that only 5 trails are sufficient to locate the best solution.

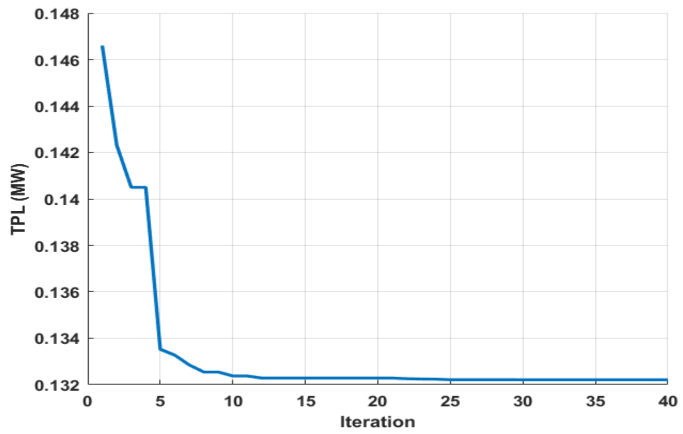

Fig. 5 Convergence characteristic of TPL minimization: case 1

Table 1 Optimized decision variables based three STATCOM: case 1: RDN 33-Bus

Methods [**3, 5**]	Limits of V (p.u)	Location of SCs	SCs size (KVAR)	Min Voltage (p.u)	TPL (KW)	TDV (p.u)
PSGA	[0.95 1.05]	6 28 29	1200 760 200	0.9463	135.4	-
GSA	[0.95 1.05]	13 15 26	450 800 350	0.9672	134.5	-
SA	[0.95 1.05]	10 14 30	450 900 350	0.9591	151.75	-
IP	[0.95 1.05]	9 29 30	450 800 900	0.9501	171.78	-
FPA	[0.95 1.05]	6 9 30	250 400 950	0.9365	171.78	-
MFO	[0.95 1.05]	8 13 30	450 300 900	0.9400	134.0725	-
GWO	[0.95 1.05]	8 13 30	450 300 900	0.9400 Bus 18	134.0725	-
DFO	[0.95 1.05]	8 13 30	450 300 900	0.9400 Bus 18	134.0725	-
PSO	[0.95 1.05]	8 13 30	450 300 900	0.9400 Bus 18	134.0725	-
WSA	[0.95 1.05]	14 24 30	397.3 451.1 1000	0.951 Bus 18	130.912[a]	
Proposed IAFT	[0.9 1]	**14** **24** **30**	361.10 547.20 1043.7	0.9389 **Bus 18**	**132.2102**	-
Proposed IAFT	[0.95 1.05]	**14** **24** **30**	**358.70** **541.90** **1036.3**	**0.9601** **Bus 18**	**126.5868**	**0.5129**

5.1.2. Case 2: TPL improvement based three DGs units under normal condition

The main objective of this second test case is to show the impact of integration only three DGs units without considering the reactive power support of shunt compensators based DSTATCOM devices. The maximum size of each DG unit is 2 MW. It is found that by integrating three DGS at buses 14, 24 and 30, the TPL is reduced to a competitive value 70.6725KW when the voltage magnitude at all PQ buses taken in the range [0.95 1.05] p.u, and by considering the limits of voltages at PQ buses in the range [0.9 1] p.u, the optimized TPL becomes 71.4572 KW. Detailed optimized results of this case are shown in Table 2, the obtained results are compared to various competitive metaheuristic methods such as FWA, BFOA, HSA, TM, GA/PSO, PSO, GA, and Water cycle algorithm (WCA), it is clearly evident, that the proposed IAFT achieves better solution at competitive number of iteration and trials. The lowest voltage magnitude is 0.95 reported at Bus 18. The convergence behaviours of TPL are shown in Figs 6-7.

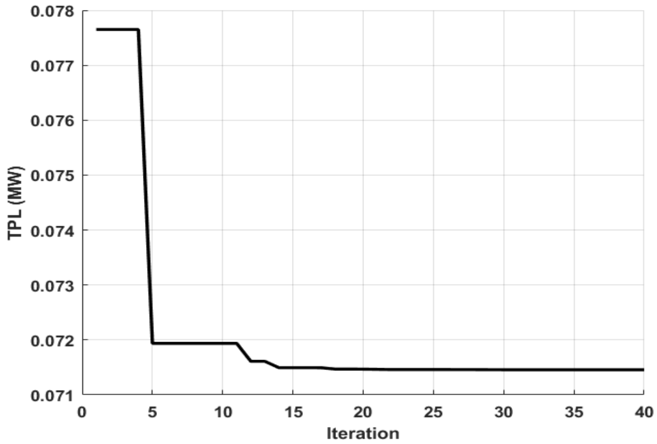

Fig. 6 Convergence characteristic of TPL minimization: case 2, Vϵ [0.9 1] p.u

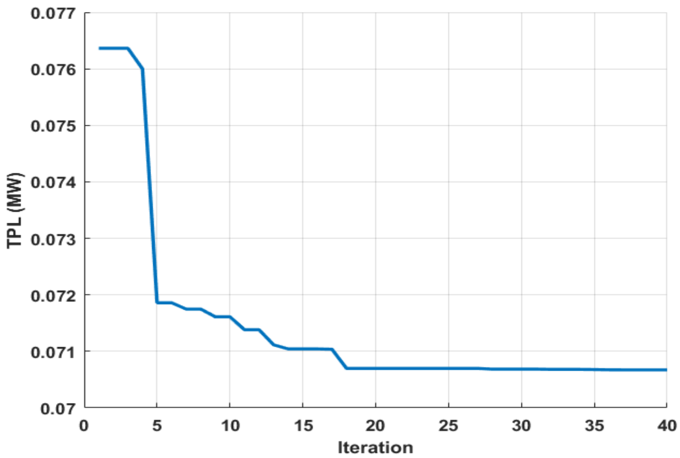

Fig. 7 Convergence characteristic of TPL minimization: case 2, Vϵ [0.9 1] p.u

Table 2 Optimized decision variables based three DGs: case 2: RDN 33-Bus

Methods [**3, 5, 27**]	Location of DGs	DGs size (KW)	Min Voltage (p.u)	TPL (KW)	TDV (p.u)
FWA	14 18 32	589.70 189.00 1014.6	0.968	88.68	-
BFOA	17 18 33	633.00 90.00 947.00	0.964	98.3	-
HSA	17 18 33	572.4 107.0 1046.2	0.967 Bus 29	96.76	-
TM	15 25 33	587.6 195.9 783.0	0.958 Bus 30	91.305	-
GA/PSO	11 16 32	925.0 863.0 1200	0.980 Bus 25	103.4	-
PSO	8 13 32	1176.8 981.60 829.70	0.980 Bus 30	105.35	-
GA	11 29 30	1500.0 422.8.0 1070.0	0.981 Bus 25	106.3	-
WSA	14 24 30	854.60 1101.7 1181.0	0.973 Bus 33	71.052	-
LSF	18 33 25	720 810 900	-	85.07	-
Fuzzy-IAS	32 30 31	2071 1113.8 150.3	-	117.36	-
BSOA	13 28 31	632 486 550	-	89.05	-
BFOA	14 25 30	779 880 1083	-	73.53	-
TLBO	10 24 31	824.6 1031.1 886.2	-	75.54	-
QOTLBO	12 24 29	880.8 1059.2 1071.4	-	74.10	-
SIMBO-Q	14 24 29	763.8 1041.5 1135.2	-	73.4	-
QSIMBO-Q	14 24 30	770.8 1096.5 1065.5	-	72.8	-
HHO	14 24 30	745.69 1022.69 1135.78	-	72.98	-
IHHO	14 24 30	775.54 1080.83 1066.69	-	72.79	-
Proposed IAFT	**14** **24** **30**	**754.00** **1099.7** **1071.4**	**0.9687** **Bus 33**	**71.4572**	**0.5872**
Proposed IAFT	**14** **24** **30**	**748.90** **884.60** **1072.3**	**0.9771** **Bus 33**	**70.6726**	**0.3224**

5.1.3. Case 3: TPL improvement based DGs units and DSTATCOM under normal condition

In this test case, three DGs and three DSTATCOM are integrated at buses 14, 24 and 30. The proposed IAFT is designed to optimize the amount of active powers of DGs and the reactive powers of DSTATCOM to be exchanged with the electric network. The optimal TPL achieved is 11.60 KW which is significantly improved compared to the last two cases and also compared to the results achieved using many recent methods such as, BFOA, WCA, TSA, ITSA, EGWA, MRFA, and JFSA. Details of optimized control variables are depicted in Table 3. The convergence characteristics for TPL minimization under two levels of penetration (76.72 % and 74.47 %) of DGs are shown in Figs 8-9, respectively, the lowest voltage magnitude is reported at bus 8.

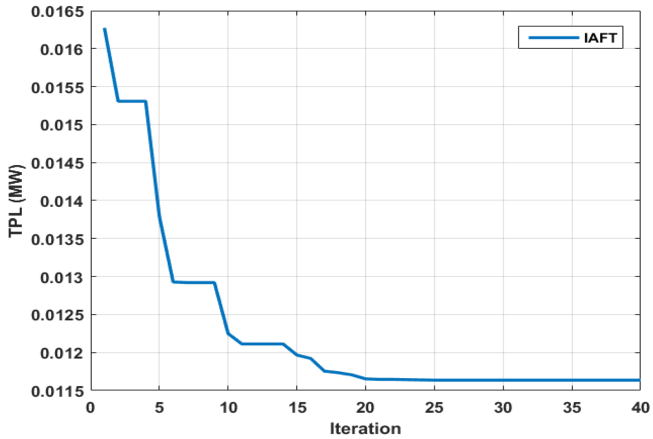

Fig. 8 Convergence behavior of TPL improvement considering 3 DGs and 3 DSTATCOM devices: Penetration level=76.72 %: RDN 33-Bus

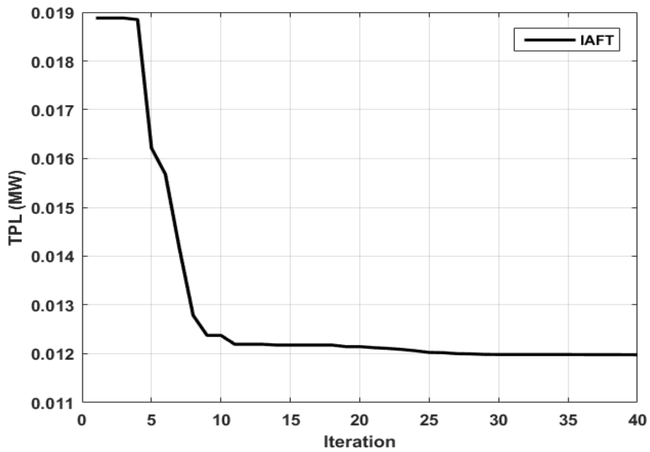

Fig. 9 Convergence behavior of TPL minimization considering 3 DGs and 3 DSTATCOM devices, Penetration level= 74.47 %: RDN 33-Bus

Table 3 Optimized decision variables based three STATCOM and three DGs units: case 3: RDN 33-Bus

Methods [4]	DGs Penetration level %	Limits of V (p.u)	Location of DGs	DGs size (KW)	Location of SCs	SCs size (KVAR)	Min Voltage (p.u)	TPL (KW)	TDV (p.u)
BFOA	42.98	[0.95 1.05]	17 18 33	542 160 895	18 33 30	163 338 541	0.9783	41.41	-
WCA	68.61	[0.95 1.05]	25 29 11	973 1040 536	23 30 14	465 565 535	0.98	24.68	-
TSA	71.57	[0.95 1.05]	24 30 12	766 917 976	30 11 24	1060 246 566	NR	15.0	-
ITSA	70.39	[0.95 1.05]	13 25 30	788 742 1085	7 15 30	603 269 834	NR	14.4	-
EGWA	76.096	[0.95 1.05]	24 14 30	1094.96 767.74 964.22	25 14 30	388.75 334.77 1189.91	0.9924	12.7	-
MRFA	78.5	[0.95 1.05]	13 24 30	803 1073 1040	14 24 30	300 600 900	0.992	12.572	-
JFSA	77.6	[0.95 1.05]	14 24 30	748 1079 1056	14 24 30	300 600 900	0.992	12.40	-
Proposed IAFT	**76.72**	[0.9 1]	**14** **24** **30**	743.9 1066.7 1039.7	**14** **24** **30**	348.2 510.8 1014.6	**Bus 8**	**11.60**	0.1284
Proposed IAFT	**74.47**	[0.9 1]	**14** **24** **30**	771.7 999.6 995.4	**14** **24** **30**	314.7 610.5 1076.5	**Bus 8**	**12.01653**	0.1287
MC					**1**				

5.1.4. Case 4: Improvement TPL and margin capacity based DGs and DSTATCOM devices

This test case is dedicated to improve the technical performances of RDN under critical situation at loading margin satiability. The TPL is optimization in coordination with the LC. For fair comparison with the third test case, three DSTATOCM and three DGs units are integrated on three optimal locations (14-24-30). The TPL optimized and the MC achieved are 71.311 kW and 2.2 p.u, respectively, the corresponding voltage deviation becomes 0.2889 p.u. The minimum voltage magnitude obtained is 0.9812 p.u reported at Bus 8. Table 4 shows the values of optimized decision variables such as the

Table 4 Optimized decision variables obtained by optimizing the TPL and MC of the RDN 33-Bus

Methods	DGs Penetration level %	Limits of V (p.u)	Location of DGs	DGs size (KW)	Location of SCs	SCs size (KVAR)	Min Voltage (p.u)	TPL (KW)	TDV (p.u)
Proposed IAFT	-	[0.9 1]	**14** **24** **30**	1786.10 1999.90 1999.90	**14** **24** **30**	607.30 1666.70 2661.20	**0.9812** **Bus 8**	**71.3110**	0.2889
MC					**2.2**				

active powers of DGs units and the reactive powers delivered by the STATCOM devices. The convergence behavior of TPL under loading margin stability is shown in Fig. 10.

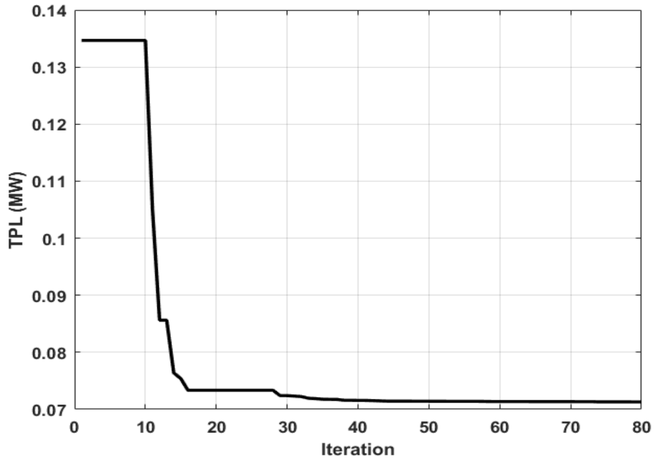

Fig. 10 Convergence behaviour of TPL improvement under MC maximization considering 3 DGs and 3 DSTATCOM devices

5.2. Test 2: RDN 69-Bus

The proposed IAFT is also validated on a medium RDN, the 69-Bus. All data of this second test system are given in [2, 31]. This second test system consists of 69 bus and 68 branches, with 12.66 kV, the total apparent power to satisfy to loads is (*3.8+j2.69*) MVA. The exploitation states of this test system at normal condition without integration of compensators and without installation of DGs are: the total power loss 224.95 KW and the low voltage magnitude is 0.9092 (p.u) reported at bus 65. The one line representation of the RDN 69-Bus is shown in Fig 11.

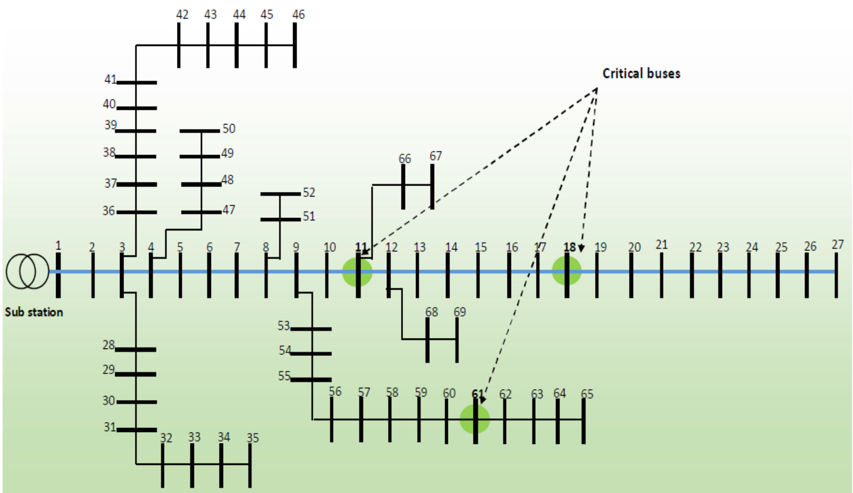

Fig. 11 Topology of the RDN 69-Bus

5.2.1. Case 5

For fair comparison with other recent technique, this test case is focused to minimize the TPL at normal condition. Three DGs and three STATCOM devices are optimally integrated at efficient locations (bus 11, bus 18 and bus 61). The sizes of DGs and STATCOM devices are 2 MW, and 1.5 MVAR, respectively. The obtained optimized variables such as the active power of DGs and the reactive power of the three STATCOM devices are recapitulated in Table 5. The best TPL achieved using IAFT is 4.2693kW, which is better than several recent techniques such as: TSA, SMA, CSO, ITAS, and JFA. The convergence behaviour of the IAFT for TPL minimization is shown in Fig 12, the distribution of voltage profile is shown in Fig 13. It is absolutely clear, that the proposed variant namely IAFT achieves the best solution quality, at a reduced time. For this test system, the population size is 10, and the maximum number of iteration is 40.

Table 5 Comparison of optimized decision variables obtained using IAFT and other techniques: Case 5: RDN 69-Bus

Methods [5]	DGs Penetration level %	Limits of V (p.u)	Location of DGs	DGs size (KW)	Location of SCs	SCs size (KVAR)	Min Voltage (p.u)	TPL (KW)
TSA	65.97	[0.95 1.05]	9 16 61	452 555 1500	21 53 61	299 605 1148	-	6.9
SMA	58.78	[0.95 1.05]	16 30 61	497 112 1625	2 13 61	708 623 1091	-	9.0053
CSO	67.42	[0.95 1.05]	17 71 67	535 1728 299	61 67 68	1367 311 323		7.5488
ITSA	60.05	[0.95 1.05]	10 12 61	291 491 1500	9 23 61	288 292 1149	0.9944	6.8012
JFSA	67.05	[0.95 1.05]	11 18 61	495 379 1674	18 51 61	300 300 1200	0.994	4.6826
Proposed IAFT	**67.15**	[0.95 1.05]	**11 18 61**	**498.8 379.3 1673.9**	**11 18 61**	**365.7 249.8 1196.3**	**0.9943 Bus 50**	**4.2693**

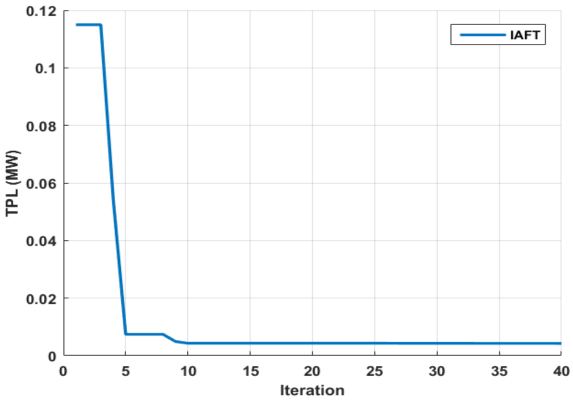

Fig. 12 Convergence behaviour of TPL improvement considering 3 DGs and 3 DSTATCOM devices: RDN 69-Bus

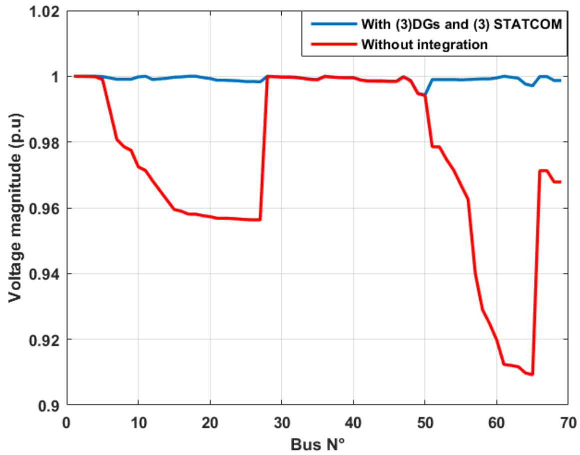

Fig. 13 Voltage profile after integration of three DGs and three DSTATCOM: RDN 69-Bus

5.3. Statistical Analysis

The performances of the proposed variant are demonstrated by elaborating a statistical analysis. The mean, the max and the standard deviation (SD) are the three well known statistical indexes used largely to identify the advantages and the drawbacks of many metaheuristic optimizers, for the first analysis five trials, and ten trials are elaborated. For all accomplished test cases, the maximum number of iterations is fixed to 40, and the population size is taken 10, the SD achieved for 10 trials is 4.3546E-6 which is remarkably better than the SD associated to a new metaheuristic namely JFSA (0.7146). Fig. 14 shows the convergence characteristics for TPL achieved for 10 trails; however the evolution of the optimized value TPL for 10 trials and 5 trials are shown in Figs.15-16, respectively. It is evident that the global solution achieved at a reduced number of trials. Table 6, depicts the statistical values achieved by using the proposed variant namely IAFT.

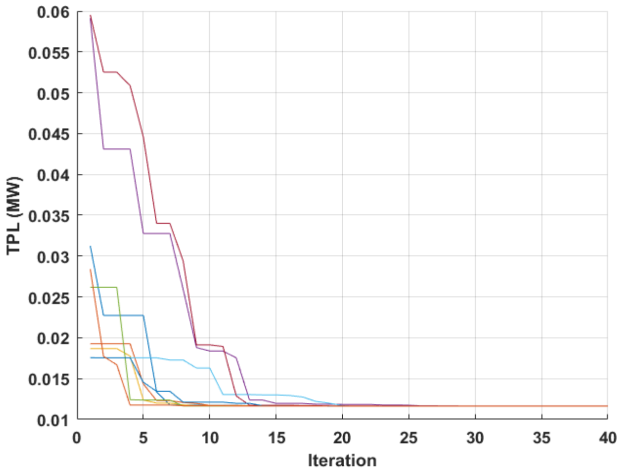

Fig. 14 Convergence behavior of TPL minimization for 10 trials; pop_size=10

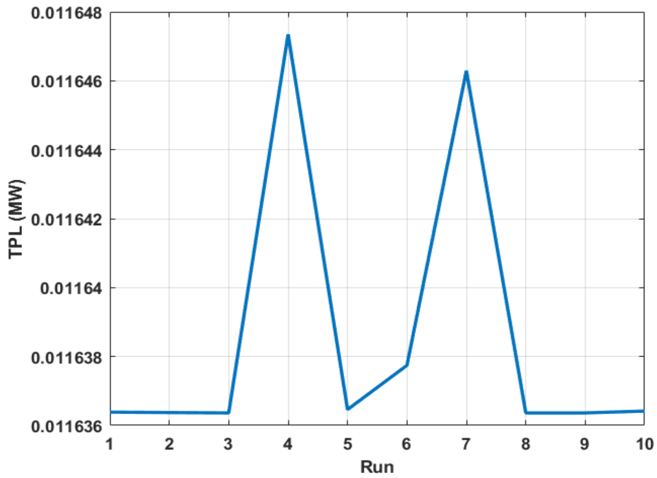

Fig. 15 Values of optimized TPL for10 trials: pop_size=10

Table 6 Robustness evaluation of optimized results: case 1: RDN 33-Bus

Scenario 1: **3** DSTATCOM and **3** DGs								
Methods	Pop_size	Max_It	Limits of V (p.u)	Min_TPL (kW)	Mean_TPL (kW)	Max_TPL (kW)	STD	Trials
Base case	-	-	-	316.2	-	-	-	-
JFSA	-	-	[0.95 1.05]	12.4002	13.1092	15.1889	0.7146	-
Proposed IAFT	5	40	[0.9 1]	**11.6366**	**12.0971**	**13.9252**	**0.001**	5
Proposed IAFT MC	10	40	[0.9 1]	**11.63636** **1**	**11.6386**	**11.64734**	**4.3546e-06**	10

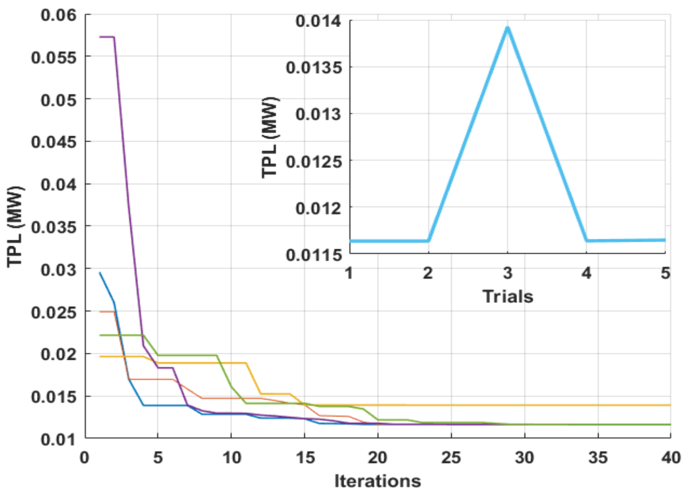

Fig. 16 Convergence behavior of TPL for 5 trials: pop_size=10

6. Conclusion

In this current study, a new variant namely IFTA is successfully adapted and applied to solve with accuracy the optimal location and setting of multi DGs units and multi shunt compensators based DSTATCOM devices. To improve the technical performances of RDN, two objective functions are optimized, the TPL and the loading margin capacity of the RDN. The TPL decreased to a competitive value 11.6473 KW when considering both three DGs and three DSTATCOM devices. The loading capacity of the RDN 33-Bus is optimized to 2.2 without affecting the operation constraints. Otherwise, the particularity of the proposed strategy is also demonstrated in optimizing the active and reactive powers of DGs and DSTATCOM devices considering the uncertainties in loads for 24 hours. It has been clearly demonstrated that the proposed power management strategy based IFTA almost gives better results in terms of solution quality and convergence behavior compared to many recent optimization algorithms. A statistical analysis demonstrated that for the RDN 33-Bus, only 5 trials are sufficient to locate the near global solution, as a result the average execution time required will be reduced at a competitive value. The proposed metaheuristic variant namely IFTA may be considered as a competitive optimizer tool to solve various power management problems of large RDN. In future work, the application of the proposed optimizer tool based IFTA will be adapted to solve the stochastic multi objective power management considering various types of FACTS devices and renewable sources.

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