Backtracking Search Algorithm With Single and Multi-Objective Function for the Solution of Optimal Power Flow Problem

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ABSTRACT

This paper investigates the performance of the backtracking search algorithm (BSA) to minimize various objectives for an economical and secure power system. A variety of single and multi-objectives are delineated and solved. This paper also includes the valve-point loading effect alongside the objectives considered. The simulation has been computed in the IEEE 30-bus, IEEE 57-bus, and IEEE 118-bus test network. The simulation outcomes as obtained by the proposed BSA and various algorithms are compared. Convergence curves are plotted to testify the characteristics of the proposed BSA for proceeding towards the global minima.

KEYWORDS

Backtracking Search Algorithm, Genetic Operator, Multi-Objective, Optimal Power Flow (OPF), Single Objective

INTRODUCTION

It is a prime goal of the power system engineer to ensure economic and secure functioning of a specific power network. Since 1980, deregulation has been taking place over the world to overcome different challenges of the power system such as economic power generation, capacity shortage, transmission congestion, power outages, transmission line losses, and environmental issues. Apart from these challenges, active power generation cost is also affected by some practical issues such as valve-point loading and prohibited zone (Mahdad et al. 2010; Mukhrjee and Mukherjee, 2016). The optimal power flow method takes a major decisive role in order to address these challenges. Principally, the OPF method optimizes the control variables, considering some mathematical constraints (Abido, 2002; Abou et al. 2009). The OPF method is a multimodal iterative method, minimizes the non-linear, non-convex objective of a particular problem. OPF method deals with both single objective and multi-objective function. A multi-objective OPF method offers a more pragmatic perspective in view of the real world power system requirements. For instance, optimization of active power generation cost causes undesired bus-voltage profile. This drawback is minimized in multi-objective optimization, where different conflicting objectives are simultaneously optimized.

Techniques to solve OPF method are fallen into two groups. The first group is conventional optimization techniques and the second one is the evolutionary algorithms. Some conventional optimization techniques are newton method (Vincovic and Mihalic, 2009), linear programming (LP)
(Al-Muawesh and Quamber, 2008), nonlinear programming (NLP) (Momoh et al. 1999). But these conventional techniques show some limitations in solving non-linear, non-convex, highly constrained, discrete optimization problems.

In order to cope with these difficulties, population-based evolutionary algorithms have played a leading role in solving OPF problems since last two decades. Genetic algorithm (GA) is an evolutionary algorithm, was discussed in the literature (Osman et al. 2005). But due to some drawbacks such as premature convergence, slow convergence characteristics and difficulty to handle highly epistatic objective functions, GA cannot give satisfactory results every time (Abido, 2002). In (Abido, 2002), the author applied particle swarm optimization (PSO) to optimize different cost and voltage objectives in a small scale electrical system. Despite its robust and efficient problem-solving capability, PSO cannot sometimes exceed local optima, which is why the researchers have adopted its modified version known as modified particle swarm optimization (MPSO) (Karami, 2015). Differential evolution (DE) algorithm, which is inspired by natural evolutionary phenomenon, was implemented by El-Fergany and Hasanien in (El-Faragany and Hasanien, 2015) to solve various cases in different electrical systems. After some modifications, DE is known as the modified DE (MDE) and was applied by the authors to solve the cost of active power generation (Sayah and Zehar, 2008). Another variant of DE is multi-objective forced initialized differential evolution algorithm (MO-DEA) is highly reliable for its high convergence speed, and it applies a new search mechanism for obtaining a well-distributed pareto optimal front (El-Sehiemy et al. 2016). Moreover, to have greater flexibility in solving optimization problem adaptive real coded biogeography-based optimization (ARCBBBO) is developed in (Kumar and Premalatha, 2015). The literature review shows another example of the population-based algorithm, namely teaching-learning-based optimization (TLBO) (Rao et al. 2012; Bouchekara et al. 2014). Adaryani et al. applied artificial bee colony (ABC) to optimize various multi-objectives in power systems of small, medium and large scale (Adaryani and Karami, 2013). In (Narimani et al. 2013) more than one objective was solved simultaneously, by using hybrid modified PSO and the shuffle frog leaping algorithms (HMPSO-SFLA). In (Reddy et al. 2014), the inadequacy of the evolutionary algorithms was addressed by the application of the efficient evolutionary algorithm (EEA), which implements a sensitivity based power flow model followed by the incremental approach. Some more population-based evolutionary techniques are mentioned in literature review i.e. grey wolf optimizer (GWO) (El-Feragany and Hasanien, 2015), differential search algorithm (DSA) (Abaci and Yamacli, 2016), moth-flame optimization (MFO) (Mirjalili, 2015), fuzzy harmony search algorithm (FHSA) (Pandiarajan and Babulal, 2016), improved colliding bodies optimization (ICBO) algorithm (Bouchekara et al. 2016), improved electromagnetism-like Mechanism (IEM) method (Bouchekara et al. 2016), hybrid PSO and GSA (PSOGSA) (Radosavljevic et al. 2015), flower pollination algorithm (FPA) (Yang, 2012), hybrid shuffle frog leaping algorithm and simulated annealing (HSFLA-SA) (Niknam et al. 2012), PSO with an aging leader and challengers (ALC-PSO) (Singh et al. 2016), modified gaussian bare-bones imperialist competitive algorithm (MGBICA) (Ghasemi et al. 2015), gbest guided artificial bee colony (GABC) optimization algorithm (Roy and Jadhav, 2015), hybrid of imperialist competitive algorithm and teaching learning algorithm (MICA–TLA) (Ghasemi et al. 2014), moth swarm algorithm (MSA) (Mohamed et al. 2017).

According to the literature survey, population-based evolutionary algorithms solve a variety of power system objectives, although these evolutionary algorithms encountered some difficulties such as– poor quality solution, inadequate balance between exploration and exploitation and weak convergence efficiency. In this regard, it is worth noting that evolutionary algorithms, which are a subcategory of heuristic techniques, are not always capable of providing an optimal solution, and this can be justified with the help of no free lunch (NFL) theory (Dokerglu et al. 2014). The success rate of an effective evolutionary algorithm is due to its speed of rapid convergence, its ability to manage complex problems and its capability to minimize objective function to a considerable degree. Due to its stochasticity, the global minimum solution point cannot be guaranteed by evolutionary algorithms. The key challenge for a researcher is therefore to select and implement a specific evolutionary
algorithm that can produce a quality solution that may or may not be global optimal, by addressing several mathematical complexities of the problem considered in a less computational time. A very new, efficient, simple and robust population-based evolutionary technique namely BSA is proposed in this manuscript to minimize several objectives.

The key attributes of the manuscript is-

a. A variety of single and multiple power system operational objectives are addressed.

b. A most recent population-based evolutionary technique namely BSA is proposed to solve power system objectives.

c. A very efficient constraint-handling mechanism is considered in the manuscript to render quality solution-set.

d. The present manuscript also focuses voltage profile aspects of different test networks to overcome operational hazards.

e. Small, medium and large test networks are taken into account to validate the problem-solving ability of BSA.

The remaining manuscript contains various units. In unit 2 the objective functions are discussed. The epitome of proposed BSA along with the operational details is included in unit 3. Unit 4 describes the operational steps of BSA-OPF. Unit 5 presents comparative discussion on simulation results. Section 6 concludes the entire work carried out in this manuscript.

2 MATHEMATICAL FORMULATION AND REPRESENTATION OF THE OPF-OBJECTIVES

From economic and security viewpoint of an electrical system, the OPF problem is formulated and is shown below,

Minimize \( J(x, u) \) \hspace{1cm} (1)

Subject to-

\( e(x, u) = 0 \) \hspace{1cm} (2)

\( p(x, u) \leq 0 \) \hspace{1cm} (3)

where, \( J(x, u) \) refers to the minimization objective; \( e(x, u) \) and \( p(x, u) \) imply equality and inequality constraint. Dependent and control variables \( x \) and \( u \) are represented by the following row vectors.

\[
x^T = [P_{g_1}, V_{l_1}, ..., V_{l_a}, Q_{g_1}, ..., Q_{g_a}, S_{L1}, ..., S_{LT}]
\]

(4)

Where, \( x \) is the vector representation of the dependent variables; \( P_{g_i} \) expresses the active power delivered by the slack bus; \( V_{l_i} \) refers to the voltage corresponding to the load bus; \( Q_{g_i} \) is the variable that signifies the generated reactive power; \( S_{TL} \) shows the loading of the interconnecting lines that
connect different buses; \( LB \), \( GB \) and \( TL \) are considered as the total number of load bus, generator bus, and transmission line correspondingly.

\[
u^T = [P_{g1} ... P_{gGB}, V_{g1}, ..., V_{gNT}, T_{c1}, ..., T_{cSC}, Q_{c1}, ..., Q_{cSC}] \tag{5}
\]

where, \( u \) corresponds to a row vector that contains produced active power \( P_g \) excluding slack bus; voltage \( V_g \) that corresponds to the voltage of the generator bus; \( T_c \) is the tapping adjustment of the regulating transformer; and \( Q_{cSC} \) expresses the amount of reactive power boosted by the parallel compensator; \( GB \) quantifies total generator buses; \( NT \) and \( SC \) represents the total regulating transformers, and parallel reactive compensators.

### 2.1 Constraints Of Equality

The following equations are deemed to be constraints of equality.

\[
\sum_{i=1}^{BN} (P_{gi} - P_{di}) = \sum_{i=1}^{BN} \sum_{j=i}^{j=1} (V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i)) \tag{6}
\]

\[
\sum_{i=1}^{BN} (Q_{gi} - Q_{di}) = -\sum_{i=1}^{BN} \sum_{j=i}^{j=1} (V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i)) \tag{7}
\]

where, \( BN \) symbolizes the total number of buses; \( P_{gi} \) and \( P_{di} \) are the generated active power and load requirement for the \( i^{th} \) bus; the generated reactive power by the \( i^{th} \) generator bus is \( Q_{gi} \) and the reactive power requirement for the \( i^{th} \) generator bus is \( Q_{di} \) correspondingly; \( i^{th} \) and \( j^{th} \) bus has the corresponding voltage value of \( V_i \) and \( V_j \); the line admittance between the \( i^{th} \) and \( j^{th} \) bus is \( Y_{ij} \); \( \theta_{ij} \) represents the angle of \( Y_{ij} \); correspondingly, for the \( i^{th} \) and \( j^{th} \) bus voltages, the phase angle representation is \( \delta_i \) and \( \delta_j \).

### 2.1.2 Constraints Of Inequality

a) Constraints accounting for the generator:-

\[
\begin{align*}
P_{gMIN}^{MIN} & \leq P_{g_i} \leq P_{gMAX}^{MAX} \\
Q_{gMIN}^{MIN} & \leq Q_{g_i} \leq Q_{gMAX}^{MAX} \\
V_{gMIN}^{MIN} & \leq V_{g_i} \leq V_{gMAX}^{MAX}
\end{align*} \quad i = 1,2, ..., GB \tag{8}
\]
where, $P_{g_i}^{MIN}$ and $P_{g_i}^{MAX}$ both correspond to the limit values of the generated active power by the $i^{th}$ generator bus respectively; $Q_{g_i}^{MIN}$ and $Q_{g_i}^{MAX}$ are the reactive power limits produced correspondingly by the $i^{th}$ generator; $V_{g_i}^{MIN}$ and $V_{g_i}^{MAX}$ correspond to the minimum and maximum boundary values of the $i^{th}$ generator bus voltage.

Constraints accounting for the tap-setting

$$T_{c_i}^{MIN} \leq T_{c_i} \leq T_{c_i}^{MAX} \quad i = 1, 2, \ldots, NT$$ (9)

where, the limit values of the tap-setting ratio for the $i^{th}$ regulating transformer is $T_{c_i}^{MIN}$ and $T_{c_i}^{MAX}$.

c) Constraints accounting for the parallel reactive compensator

$$Q_{c_i}^{MIN} \leq Q_{c_i} \leq Q_{c_i}^{MAX} \quad i = 1, 2, \ldots, SC$$ (10)

where, the $i^{th}$ parallel compensator is operated within arrange of $Q_{c_i}^{MIN}$ and $Q_{c_i}^{MAX}$.

Constraints accounting for the security concern

$$V_{l_i}^{MIN} \leq V_{l_i} \leq V_{l_i}^{MAX} \quad i = 1, 2, \ldots, LB$$ (11)

$$S_{l_i} \leq S_{l_i}^{MAX} \quad i = 1, 2, \ldots, TL$$ (12)

where, the $i^{th}$ load bus voltage is bounded by $V_{l_i}^{MIN}$ and $V_{l_i}^{MAX}$. $S_{l_i}^{MAX}$ represents the maximum loading of $i^{th}$ transmission line.

2.2. Constraints Handling Method

This method is very important to have feasible solutions of the OPF problem (Mohamed et al. 2017). Dependent variables such as $P_{g_i}$, $V_i$, $Q_g$, $S_l$ are not self-constrained. Therefore, these variables are included in the objective as a quadratic penalty component in order to produce viable solutions. The penalty component is given below,

$$Penalty = \lambda_{P} \left( P_{g_i} - P_{g_i}^{LIM} \right)^2 + \lambda_{Q} \sum_{i=1}^{GB} \left( Q_{g_i} - Q_{g_i}^{LIM} \right)^2 + \lambda_{V} \sum_{i=1}^{LB} \left( V_i - V_{L_i}^{LIM} \right)^2 + \lambda_{S} \sum_{i=1}^{TL} \left( S_{l_i} - S_{l_i}^{MAX} \right)^2$$ (13)
where, \( \lambda_{P_{i}}, \lambda_{Q_{i}}, \lambda_{V_{i}}, \) and \( \lambda_{S_{i}} \) refer the multiplying factor to evaluate penalty component. \( X^{LIM} \) indicates the upper or lower limit of \( X \), which is a dependent variable and is not within the prescribed boundary. \( X^{LIM} \) is defined below,

\[
X^{LIM} = \begin{cases} 
X^{MAX} ; X > X^{MAX} \\
X^{MIN} ; X < X^{MIN} 
\end{cases}
\]  

(14)

2.3. Objective Function

This manuscript takes into account two types of objective functions, single and multi-objective.

2.3.1 Function With One Objective

(a) Production cost of active power

Required fuel-cost to generate active power corresponding to the \( i^{th} \) bus is a mathematical function that follows quadratic pattern and is formulated below,

\[
J_{1} = \left( \sum_{i=1}^{GB} u_{i} P_{g_{i}}^{2} + v_{i} P_{g_{i}} + w_{i} \right) + \text{Penalty} (\$/hr) 
\]  

(15)

where \( u_{i} \), \( v_{i} \) and \( w_{i} \) represent the multiplying factor for calculating the required fuel cost corresponding to the \( i^{th} \) thermal generator.

(b) Production cost of active power taking into account the phenomenon of valve-point loading

The valve-point loading phenomenon which causes huge deviation in active power production cost is observed in steam turbine with multiple-valve. This phenomenon makes the active power production cost non-linear and discontinuous. Thermal generators 1 and 2 show valve-point loading effect and the cost function for this effect is expressed as follows,

\[
J_{v\_cont} = \sum_{i=1}^{2} \left| d_{i} \times \sin(e_{i} \times (P_{g_{i}}^{MIN} - P_{g_{i}})) \right| + \text{Penalty} \ (\text{Ton/hr}) 
\]  

(16)

where, \( d_{i} \) and \( e_{i} \) are the multiplying factor for the cost accounted due to the valve-point loading phenomenon. Production cost of active power taking into account the phenomenon of valve-point loading is expressed by mathematically as shown below,

\[
J_{2} = \left( \sum_{i=1}^{GB} a_{i} P_{g_{i}}^{2} + b_{i} P_{g_{i}} + c_{i} + | d_{i} \times \sin(e_{i} \times (P_{g_{i}}^{MIN} - P_{g_{i}})) | \right) + \text{Penalty} \ (\text{Ton/hr}) 
\]  

(17)

(c) Emission level
Thermal power plants emit some pollutant gasses such as NOx and SOx. This has a detrimental effect on the environment. The mathematical formulation for the emission objective exhibits a polynomial, quadratic expression that contains exponential terms, is given in the next equation.

\[
J_3 = (\sum_{i=1}^{GB} \gamma_i P_{s_i}^2 + \beta_i P_{s_i} + \alpha_i + \varepsilon_i \exp(\lambda_i P_{s_i})) + \text{Penalty} \left( \text{Ton} / \text{hr} \right)
\]

In the above equation the multiplying factor to calculate the emission level are taken as, \(\gamma_i\), \(\alpha_i\), \(\beta_i\), \(\xi_i\) and \(\lambda_i\).

(d) The loss of power transmission line

Transmission line loss minimization is a key objective for the plant operator. The objective function for the transmission line loss minimization is formulated below,

\[
J_4 = \sum_{n=1}^{TL} G_n [ |V_i|^2 + |V_j|^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j) ] + \text{Penalty} \left( \text{Ton/hr} \right)
\]

where, the \(n^{th}\) line connecting \(i^{th}\) and \(j^{th}\) bus, has a conductance of \(G_n\).

2.3.2 Multi-Objective Function

Here, more than one objective is simultaneously minimized.

(a) The cost of active power production and the loss of power transmission line

The cost of active power production and the loss of power transmission line are two vital objectives to be minimized. Both of these objectives are formulated all together and is given below,

\[
J_5 = (\sum_{i=1}^{GB} a_i P_{s_i}^2 + b_i P_{s_i} + c_i) + \lambda_p \sum_{n=1}^{TL} G_n [ |V_i|^2 + |V_j|^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j) ] + \text{Penalty}
\]

In the above expression \(\lambda_p\) is the weighting factor and its value is 40.

(b) The cost of active power production along with bus voltage profile

Two unlike objectives, which are the cost of active power production and load bus voltage, are considered here together. Consistent voltage of the load bus is a really imperative factor of any power network that ensures safety margin. Minimizing this objective ensures less voltage fluctuation of the load bus. Below is the extent of the change in load bus voltage with respect to the reference value.

\[
J_{VD} = \sum_{i=1}^{LB} |V_i - 1|
\]
\[ J_6 = \sum_{i=1}^{Gb} a_i P_{s_i}^2 + b_i P_{s_i} + c_i + \lambda_{VD} \sum_{i=1}^{LB} |V_{j} - 1| + \text{Penalty} \]  

(22)

where \( \lambda_{VD} \) represents the weighting factor. The value of the \( \lambda_{VD} \) is considered as 100.

(c) The cost of the active power production along with voltage stability

The operation of the power system with stable voltage magnitudes is a major concern of the system operator. Load fluctuation can lead to voltage instability and reduce bus voltage. Voltage instability keeps the power system away from its nominal operating conditions. To sort out this major problem, voltage stability index is developed and is denoted by \( L_{\text{max}} \) and is formulated below,

\[ L_{\text{max}} = \max(L_j) ; \ j = 1,2,\ldots, TL \]  

(23)

\( L_j \), which indicates the degree of the voltage instability of the \( j^{th} \) load bus and is considered as a local indicator. The following equation represents \( L_j \),

\[ L_j = \left| 1 - \sum_{i=1}^{Gb} H_{ji} \frac{V_i}{V_j} \right| ; \ j = 1,2,\ldots, TL \]  

(24)

where \( H_{ji} \) refers the partially inverted form of \( Y_{BUS} \) matrix. Minimization of \( L_{\text{max}} \), gives a stable system voltage and also helps the system to run without any voltage disruption.

A multi-objective function is formulated, given in equation (25), which simultaneously minimizes the quadratic fuel cost of the active power generations and the voltage stability index.

\[ J_7 = \left( \sum_{i=1}^{Gb} a_i P_{s_i}^2 + b_i P_{s_i} + c_i \right) + \lambda_L (\max(L_j)) + \text{Penalty} \]  

(25)

where \( \lambda_L \) is the weighting factor and fix at 100.

(d) The cost of the active power production along with emission cost, voltage deviation and the loss of power transmission line

Here a multi-objective function is considered that includes four different objectives such as the cost of active power production, emission level, voltage deviation and power transmission line loss and is given by the following equation.

\[ J_8 = \left( \sum_{i=1}^{Gb} a_i P_{s_i}^2 + b_i P_{s_i} + c_i \right) + \lambda_{EL} \left( \sum_{i=1}^{Gb} \gamma_i P_{s_i} + \beta_i P_{s_i} + \alpha_i + \varepsilon \exp (\lambda P_{s_i}) \right) + \]  

\[ \lambda_{VD} \left( \sum_{i=1}^{TL} |V_i - 1| \right) + \lambda_v \left( \sum_{n=1}^{TL} G_n (|V_i|^2 + |V_j|^2 - 2|V_i||V_j|\cos(\delta_i - \delta_j)) \right) + \text{Penalty} \]  

(26)
where, $\lambda_{EL}$, $\lambda_{VD}$ and $\lambda_{P}$ are set to 19, 20 and 22 to enhance the qualities of the solutions.

3 BSA- THE OPTIMIZATION TECHNIQUE

3.1. Outline

BSA conceptualizes a population oriented heuristic search technique, which was introduced by Civicioglu (Civicioglu, 2013). Its uniqueness lies into the mechanism of generating “trial individual”-through which it optimizes real world, complex, nonlinear optimization problems. In addition to that, it is an algorithm with a simpler structure and uses both current and old population. Three operators which are selection, mutation, and crossover, are associated with BSA. In BSA, the target individuals are guided by the direction individual, in order to get mutated. According to the search direction, the individuals are randomly chosen by the BSA, from the past-generation individuals. Five different genetic operators are associated to build the framework of BSA and they are- initialization, selection-I, mutation, crossover, and selection-II.

Initialization: This operation randomly generates the initial population $POP_{j,k}$, as given below

$$POP_{j,k} = U(Low_k,Up_k)$$  \hspace{1cm} (27)

where, $j = 1, \ldots, S$ and $k = 1, \ldots, C$ ; $S$ refers to number of population and $C$ indicates the total control variables. The limiting values, namely $Up$ and $Low$, restricts the control variables. $U$ specifies a uniform probability distribution function. Each target individual corresponding to the population $POP$ is represented by $POP_j$.

ii) Selection –I: In this step the search direction is mathematically decided by the old population, whose mathematical formation is shown below,

$$POP_{j,k}(old) = U(Low_k,Up_k)$$  \hspace{1cm} (28)

BSA creates a population first by random selection method, which is the historical population. BSA has a memory so that it remembers the old population and generates a new one by if-else loop until the historical population has been changed.

iii) Mutation: In this step another trial population has been generated by the mutant, which is shown by the equation given below,

$$Mutant = POP + F \times (oldPOP – POP)$$  \hspace{1cm} (29)

The search direction matrix is evaluated by $(oldPOP – POP)$, which is controlled by a variable $F$. In BSA, the historical population creates the search direction matrix and thereafter the trial population has been generated to take the recompense of the historical population. Here, the value of $F$ is taken as 3.
iv) Cross-over: The trial population $T$ is formed by this operator. In the previous operational phase, the preliminary value of the trial population was generated. Here, the target population individuals are formed by the trial individuals those have better fitness. The unique cross over strategy has two different stages. In first stage, in order to form binary integer matrix map with a dimension of $S \times C$, a mathematical operation takes place between the individuals of $T$ and $POP$. In second stage, one random number is selected from the mutant for every trial.

v) Selection-II: This operator runs a voracious selection process. The $T_j$ which hold better fitness values, replace corresponding $POP_j$. Thus the optimal solution has been generated. Fig.1 illustrates BSA’s basic structure.

The sequential structure of the BSA is given below-

Step 1: Start.
Step 2: Population "POP" is initialized and expressed with the following equation (30) in the search space.

$$POP_{jk} = Low_k + rand(0,1) \times (Up_k - Low_k)$$ (30)

Step 3: Here, the historical population "oldPOP" is generated, using the following equation

$$oldPOP_{jk} = Low_k + rand(0,1) \times (Up_k - Low_k)$$ (31)

Step 4: The fitness value is calculated for the each individual population, contained by the population set "POP" by the following equation,

$$Fitness(POP_j) = Obj\ Fun(POP_j)$$ (32)

Step 5: If, $a > b$ then, oldPOP := POP, here $a$ and $b$ are two random numbers between $0$ and $1$. ":=" signifies update operation.
Step 6: This step randomly alters the sequence of the individuals in "oldPOP". This operation is characterized by the following equation,

$$oldPOP = permuting(oldPOP)$$ (33)

Here, the permuting function represents a random shuffling operation.

Step 7: Scale factor $F$ is generated. The value of $F$ is $(3.randn)$ and $randn \sim N(0,1)$, where $N$ refers standard normal deviation.

Step 8: $map_{[1:S\times C]}$ is composed by binary integer values and is computed on the basis of the following logics and equations.

If, $c < d \mid c, d - rand(0,1)$ then, $map(j,u(ceil(DIM\_RATE \times rand(0,1) \times C))) = 1$
$j = 1, \ldots, S$; $u = \text{permute}(1, 2, 3, \ldots, D)$; "ceil" is the ceiling function in MATLAB; where,

$\text{DIM}_R \text{ATE} = 1$

Else, $\text{map}(j, \text{rand}(C)) = 1$
Step 9: Offspring is produced by the following equation,

\[ \text{offspring}_{jk} = \text{POP}_{jk} + (\text{map}_{ij} \times F) \times (\text{OldPOP}_{jk} - \text{POP}_{jk}) \]  (34)

\( j = 1, \ldots, S \) and \( k = 1, \ldots, C \)

Step 10: If, \((\text{offspring}_{jk} > \text{up}_k)\) or \((\text{offspring}_{jk} < \text{low}_k)\)

then, \( \text{offspring}_{jk} = \text{up}_k \) and \( \text{offspring}_{jk} = \text{low}_k \)

Else, \( \text{offspring}_{jk} = \text{low}_k + \text{rand}(0,1) \times (\text{up}_k - \text{low}_k) \) end

Step 11: If, \( \text{Fitness(POP)} > \text{Fitness(offspring)} \) then

\[ \text{POP}_{jk} = \text{offspring}_{jk} \text{ and Fitness(POP)} = \text{Fitness(offspring)} \] end

Step 12: Find and sort the best individuals of "POP".
Step 13: Terminate.

3.2 Implementation Of BSA To Solve OPF

To reach at the desired objective, BSA is employed with the OPF method. To do so, certain constraints are satisfied, by initializing \( S \) number of populations, and each population contains \( C \) number of control variables. The following steps provide the basic framework of BSA in context of the OPF problem discussed.

Step 1- At first, all the control variables except the active power of the slack bus are randomly generated by equation (28). Thereafter, the load flow is executed to have the active power of the slack bus and other dependent variables are obtained.

Step 2- The control variables of the historical population "oldPOP" are generated with the help of the equation (33). Afterward with help of the load flow the dependent variables of the "oldPOP" are computed.

Step 3- The fitness of each population is calculated by equation (34).

Step 4- The Historical population is permuted in each iteration.

Step 5- The mutation operation is done by the equation (33).

Step 6- The crossover operation is carried out.

Step 7- The trial population is generated, whose members are known as "offsprings" and hence the upper and lower boundaries of the "offsprings" are checked. Next, by executing the load flow the slack bus power and other control are obtained. Afterwards, randomly generated new solutions to replace the infeasible "offsprings"

Step 8- The fittest "offsprings" are selected, and their fitness is evaluated.

Step 9- If the fittest "offsprings" are better than the solutions of the initial population, then the fittest "offsprings" replace the solutions of the initial population else continue with the prior one.
Step 10- The latest population is arranged in best to worst manner to involve them into the next generation.
Step 11- Step 2 is repeated, unless the maximum iteration number is reached.

5 SIMULATION RESULTS

In view of three standard IEEE test network, a wide range of objectives are addressed by the implementation of BSA. To prove the efficacy and computational strength of proposed BSA, the outcomes are compared with evolutionary algorithms, which are- GA, MSA (Mohamed et al. 2017), MPSO (Mohamed et al. 2017), MDE (Mohamed et al. 2017), MFO (Mohamed et al. 2017), FPA (Mohamed et al. 2017), TLBO (Bouchemar et al. 2014), ICBO, HAS (Pandiarajan and Babulal, 2016), FHSA (Pandiarajan and Babulal, 2016), PSOGSA (Radosavljevic et al. 2015), DSA (Abaci and Yamacli, 2016), ABC (Adaryani and Karami, 2013), GABC (Roy and Jadhav, 2015), IEM (Bouchemar et al. 2016), MO-DEA (El-Sehiemy et al. 2016), MGBICA (Ghasemi et al.2015), GBCIA (Ghasemi et al.2015), HSFLA-SA (Niknam et al. 2012), EEA (Reddy et al. 2014), EGA (Reddy et al. 2014), ALC-PSO, HMPSO-SFLA (Narimani et al. 2013), MICA-TLA (Ghasemi et al. 2014), ARCBBO(Kumar and Premalatha, 2015), RCBBBO(Kumar and Premalatha, 2015), DE (El-Feragany and Hasanien, 2015), and GWO (El-Feragany and Hasanien, 2015). The software, used to carry out the simulation work is Matlab 7.8. The PC, where the simulations are done, has 2GB RAM, i3 processor and 2.20 GHz clock speed. Table 1 lists the objectives considered in this manuscript for separate simulation set-ups.

5.1 Test Network-1: IEEE 30-Bus Network

The aforementioned test network which is briefed in Table 2 is specified with a 100 MVA base, an active and reactive power requirement of 2.834 p.u and 1.262 p.u. Besides, the rest of the test network data is collected from (Alsac and Scott, 1974). The number of iterations is considered to be 100. The multiplying factors to evaluate fuel cost and emission level are listed in Table 3. Table 4 sets the limit of IEEE 30-bus network control variables.

5.1.1 Simulation set-up1

The cost for active power production is minimized in the present simulation set-up. Equation (15) represents the objective for the simulation set-up1. A clear conclusion is drawn from Table 5 that the BSA results in minimum active power generation cost (799.7221 $/h) compared to the other algorithms. The optimal active power generation costs obtained by BSA-OPF and some more algorithms are listed by Table 6. Table 7 lists the control variables obtained by the proposed BSA-OPF and MSA-OPF. Table 8 shows the statistical result and CPU time for the present simulation set-up for BSA and few other popular evolutionary algorithms. By observing Table 8 it is clearly appeared that proposed BSA is very efficient to produce statistically robust result as well it takes very less CPU time than other evolutionary algorithms.

5.1.2 Simulation set-up2

This set-up targets to minimize active power generation costs in the event of valve-point loading. Equation 17 states the mathematical formation of the present objective. Tables 5 and 6 show that the optimal cost obtained by the BSA-OPF (929.3449$/h) is slightly lower than the optimal cost obtained by other algorithms listed. Table 7 enumerates the control variables for BSA-OPF and MSA-OPF where Fig 3 shows the convergence trajectory of this set-up.
5.1.3 Simulation set-up3

Emission level is reduced in the present simulation set-up and the mathematical formulation for the same is given by equation (18). Tables 5 and 6 depict the optimal emission level attained by the proposed BSA and some listed algorithms. The simulation results confirm that the BSA-OPF produces the best result among all other listed algorithms. Further Table 7 lists the control variables of the simulation set-up discussed. The convergence feature of the current simulation set-up is shown in Fig 4.

5.1.4 Simulation set-up4

Transmission line loss plays a vital role to ensure the operational security of power system. Equation 19 represents the mathematical formulation of the transmission line loss objective. Tables 5 and 6 show a comparative illustration between the optimal solutions obtained by proposed BSA and a few more advanced algorithms. While Table 7 shows the control variables obtained in this simulation set-up. The results of Table 5 and 6 reinforce the vivid features of the proposed BSA. The convergence pattern is shown in Fig 5 for the current set-up.

5.1.5 Simulation set-up5

This simulation set-up aims to reduce two different objectives, i.e. the cost of generating active power in addition to the loss of power transmission line. Equation (20) presents the objective function for this simulation study. Table 8 represents the optimal solutions for the present simulation study. Table
9 shows that the proposed BSA notably improves the mentioned objectives compared to the other algorithms listed. In Table 9, the control variables that correspond to the best result as for BSA-OPF and MSA-OPF are shown.

5.1.6 Simulation set-up 6

This simulation set-up optimizes both the cost of generating active power and the voltage profile. The objective of the present simulation set-up is shown by equation (22). The optimum results obtained by the proposed BSA are $803.7/h and 0.1329 p.u. are given in Table 9. Furthermore, Table 10 lists the control variables achieved by the proposed BSA-OPF and MSA-OPF respectively.

5.1.7 Simulation set-up 7

In the present set-up the cost of generating active power is minimized with the voltage stability objective. Equation (25) represents the mathematical formulation of this set-up. Table 8 shows the results of the current set-up obtained by proposed BSA-OPF. Table 10 indicates the control variables for BSA-OPF and MSA-OPF, respectively. The optimal results of proposed BSA as set out in Table 9 clearly indicate the supremacy of the BSA over the other algorithms listed.

5.1.8 Simulation set-up 8

This Simulation set-up deals with the multi-objective function (equation 26), which has a trade-off between four conflicting objectives: active power generation cost, emission level, voltage deviation,
and transmission line loss. Table 9 presents the optimal objectives for the current simulation set-up. The results obtained show once again that proposed BSA results in a feasible and quality solution with a maximum reduction in active power generation cost (830.5970$/h) compared to GA (830.604 $/h), MSA (830.639$/h), MPSO (833.6807$/h), MDE (830.0942$/h), MFO (830.9135$/h) and FPA (835.3699$/h). Whereas the optimum parametric values of the control variables are listed in Table 10.

5.2 Test Network-2: Ieee 57-Bus Network

To investigate the BSA’s competence, a comparatively larger network is simulated (Zimmerman and Sanchez, 2015). The key features of this test power network are described by Table 11. The limit of the control variables is represented in Table 12. The active and reactive power requirement by IEEE 57-bus network is 12.508 p.u. and 3.364 p.u. respectively. In view of the current experimental system, the OPF is formulated with 50 number of population and is iterated 100 times. The following simulation set-ups are solved, taking into account the IEEE 57-bus network.

5.2.1 Simulation set-up9

The current set-up also reduces the cost of active power generation; similar to the simulation set-up 1. The optimal results of the proposed BSA-OPF as well as for some other algorithms are shown in Tables 13. A notable cost reduction (41622.0 $/h) is found for the proposed BSA compared to the other algorithms, such as GA (41629.93 $/h), MSA (41673.72 $/h), MPSO (41678.68 $/h), MDE (41695.81 $/h), MFO (41686.41 $/h) and FPA (41701.96 $/h). The control variables are enumerated in Table 14. Table 15 presents CPU time for BSA, GA and TLA and that are 38. 331 sec, 42.66 sec, and 44.56 sec.
respectively. It is inferred by observing the CPU time entries in Table 15 that proposed BSA has rapid processing capability. Figure 6 illustrates the convergence pattern for the present simulation set-up.

5.2.2 Simulation set-up

The current simulation set-up minimizes both the cost of generating active power with the voltage stability index as a two-fold objective function as expressed by equation (25). Table 13 shows that the cost of active power generation for the BSA is 41675$/h, whereas 41701.65 $/h for GA, 41714.99 $/h for MSA, 41721.61$/h for MPSO, 41717.39$/h for MDE, 41718.87$/h for MFO and 41726.38$/h for FPA. Table 13 also indicates clearly that the proposed BSA minimizes the voltage stability index (0.2223) appropriately compared to other algorithms such as MSA (0.29533), MPSO (0.2955), MDE (0.2952), MFO (0.29525) and FPA (0.29488). In addition, the control variables for the current simulation set-up are listed in Table 14.

5.2.3 Simulation set-up

A simultaneous minimization of two objectives ensuring an economically strengthen and secure power system is taken into account. Equation (22) describes the objective for the current set-up and Table13 lists up the results for the present set-up. Table 12 shows the control variables. Table 14 shows that the results of BSA-OPF are comparatively superior to the other listed algorithms.

5.3 Test Network-3: IEEE 118-Bus Network

It is very difficult to maintain the economic balance of a large power system and requires absolute precision of the system parameters. Owing to that fact IEEE 118-bus network is simulated to attain
optimal setting of the control variables and which further testifies the robustness of the proposed BSA. Key features of this network are presented in Table 16, and rests of the information are mentioned in (Zimmerman and Sanchez, 2015). This network’s active and reactive power requirement is respectively 42.42 p.u and 14.39 p.u. A single objective is formulated for this test power network and is given below.

5.3.1 Simulation set-up

The present study minimizes active power generation cost objective and which is shown by equation (15). In Tables 17 and 18, the optimal cost as attained by proposed BSA and other advanced algorithms are listed. By examining the results presented in Tables 17 and 18, it is clearly revealed that proposed BSA reduced active power generation cost, sufficiently compared to the other algorithms. In Table 19, the control variables of the present set-up are given. Fig 7, shows the convergence curve for the present simulation set-up.

5.4 Load Bus Voltage Profile: An Index Of Secure Power System

Figure 8-Fig 10 shows the load bus voltage profile in case of simulation set-up1 to the simulation set-up11. From the mentioned figures, it is confirmed that none of the load bus voltages cross the boundary of 0.95 p.u-1.1 p.u and 0.94 p.u to 1.06 p.u taken for IEEE 30-bus and IEEE 57-bus network. Figure 9 and 10 also confirm that a flat load bus voltage profile with a minimum deviation from 1 p.u is maintained in simulation set-ups 6, 8 and 9. As a result, it can be realized and affirmed that BSA-OPF has strict constraint handling property which ensures a secure and stable power system.
6. CONCLUSION

The outcomes drawn in the present manuscript emphasize the effective problem-solving paradigm of proposed BSA approach. From different comparative data analysis, done in this manuscript, it is understandable that proposed BSA has a unique global search strategy and this makes this algorithm superior as compared to other contemporary algorithms. To validate the competence of BSA, three different test power networks are simulated considering different power system objectives. It is evident from the results obtained in various simulation set-ups that proposed BSA can generate optimized solutions with a higher degree of viability. In addition to that the present research-work also ensures the secure operation of three different test networks in context of bus-voltage magnitude. By examining different convergence curves, drawn up in this manuscript, it can also be concluded that BSA solves the various target-objectives at a high convergence rate. It is also considered that the proposed algorithm applies to different genetic operators and benefits from solutions from the past generation to produce good quality solutions. For these sophisticated and distinct features, the proposed BSA draws the attention of the researchers to optimize non-convex, non-smooth power network optimization problems with great ability.
Figure 8. Load bus voltage profiles: simulation set-up1 — simulation set-up3

Figure 9. Load bus voltage profiles: simulation set-up5 — simulation set-up8
Figure 10. Load bus voltage profiles: simulation set-up 9 — simulation set 11
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Table 1. Different objective functions for various simulation set-ups along with operating constraints

| Simulation set-up | FOR IEEE 30 BUS NETWORK | FOR IEEE 57 BUS NETWORK | FOR IEEE 118 BUS NETWORK |
|-------------------|-------------------------|-------------------------|-------------------------|
|                   | OBJECTIVE FUNCTION      | CONSTRAINTS             | OBJECTIVE FUNCTION      | CONSTRAINTS             | OBJECTIVE FUNCTION | CONSTRAINTS             |
| Simulation set-up (1) | A.P generation cost  | Equality and            | x                      | x                      | x                      | x                      |
|                    |                         | inequality              |                         |                         |                         |                         |
| Simulation set-up (2) | A.P generation      | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost curve with valve  | inequality              |                         |                         |                         |                         |
|                    | point loading          |                         |                         |                         |                         |                         |
| Simulation set-up (3) | Emission cost        | Equality and            | x                      | x                      | x                      | x                      |
|                    |                         | inequality              |                         |                         |                         |                         |
| Simulation set-up (4) | A.P loss              | Equality and            | x                      | x                      | x                      | x                      |
|                    |                         | inequality              |                         |                         |                         |                         |
| Simulation set-up (5) | A.P generation        | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost considering       | inequality              |                         |                         |                         |                         |
|                    | active power loss      |                         |                         |                         |                         |                         |
| Simulation set-up (6) | A.P generation        | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost considering       | inequality              |                         |                         |                         |                         |
|                    | voltage profile        |                         |                         |                         |                         |                         |
| Simulation set-up (7) | A.P generation        | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost considering       | inequality              |                         |                         |                         |                         |
|                    | voltage stability      |                         |                         |                         |                         |                         |
| Simulation set-up (8) | A.P generation        | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost considering       | inequality              |                         |                         |                         |                         |
|                    | voltage stability,     |                         |                         |                         |                         |                         |
|                    | power loss and         |                         |                         |                         |                         |                         |
|                    | voltage profile        |                         |                         |                         |                         |                         |
| Simulation set-up (9) | A.P generation        | Equality and            | x                      | x                      | x                      | x                      |
|                    | cost                   | inequality              |                         |                         |                         |                         |

**NOTES:**

- A.P: Active Power
- Equality and inequality constraints indicate that both equality and inequality constraints are considered for each simulation set-up.
- "x" indicates the presence of a constraint.
### Table 1. Continued

| Simulation set-up | FOR IEEE 30 BUS NETWORK | FOR IEEE 57 BUS NETWORK | FOR IEEE 118 BUS NETWORK |
|-------------------|--------------------------|-------------------------|--------------------------|
|                   | OBJECTIVE FUNCTION       | CONSTRAINS              | OBJECTIVE FUNCTION       | CONSTRAINS |
| Simulation set-up (10) | x | x | A.P generation cost considering voltage stability | Equality and inequality | x | x |
| Simulation set-up (11) | x | x | A.P generation cost considering voltage profile | Equality and inequality | x | x |
| Simulation set-up (12) | x | x | x | Equality and inequality |

A.P generation cost
Table 2. IEEE 30 bus network: A brief representation

| Features                                | Quantity | Description                                                                 |
|-----------------------------------------|----------|-----------------------------------------------------------------------------|
| Buses                                   | 30       | (Alsac and Scott, 1974)                                                     |
| Branches                                | 41       | (Alsac and Scott, 174)                                                      |
| Generators                              | 6        | Buses-1, 2, 5, 8, 11 and 13                                                 |
| Parallel Reactive Compensator           | 9        | Buses-10, 12, 15, 17, 20, 21, 23, 24 and 29.                               |
| Tap setting of regulating Transformer   | 4        | Branches: 11, 12, 15 and 36                                                 |
| Control variables                       | 24       | ____                                                                        |

Table 3. Multiplying factors for emission and fuel cost (IEEE 30-bus network)

| Generator No. | Bus No. | Emission | Fuel cost |
|---------------|---------|----------|-----------|
|               |         | α        | β         | γ         | λ         | ξ         | u         | v         | w         |
| 1             | 1       | 0.04091  | -0.0554   | 0.0649    | 2.857     | 0.0002    | 0.0037    | 2         | 0         |
| 2             | 2       | 0.02543  | -0.0604   | 0.0563    | 3.333     | 0.0005    | 0.0175    | 1.75      | 0         |
| 3             | 5       | 0.04258  | -0.05094  | 0.04586   | 8         | 0.000001  | 0.0625    | 1         | 0         |
| 4             | 8       | 0.05326  | -0.0355   | 0.0338    | 2         | 0.002     | 0.0083    | 3.25      | 0         |
| 5             | 11      | 0.04258  | -0.0509   | 0.04586   | 8         | 0.000001  | 0.025     | 3         | 0         |
| 6             | 13      | 0.06131  | -0.555    | 0.05151   | 6.667     | 0.000001  | 0.025     | 3         | 0         |

Table 4. Control variables and their ranges (IEEE 30-bus network)

| Control variables | Min | Max  | Control variables | Min | Max  | Control variables | Min | Max  | Control variables | Min | Max  | Control variables | Min | Max  | Control variables | Min | Max  |
|-------------------|-----|------|-------------------|-----|------|-------------------|-----|------|-------------------|-----|------|-------------------|-----|------|-------------------|-----|------|-------------------|-----|------|
| P₁              | 0   | 575.9 | V₁              | 0.95| 1.1  | T₁              | 0.9 | 1.1  | T₁              | 0.9 | 1.1  | T₁              | 0.9 | 1.1  | T₁              | 0.9 | 1.1  |
| P₂              | 0   | 100  | V₂              | 0.95| 1.1  | T₂              | 0.9 | 1.1  | T₂              | 0.9 | 1.1  | T₂              | 0.9 | 1.1  | T₂              | 0.9 | 1.1  |
| P₃              | 0   | 140  | V₃              | 0.95| 1.1  | T₃              | 0.9 | 1.1  | T₃              | 0.9 | 1.1  | T₃              | 0.9 | 1.1  | T₃              | 0.9 | 1.1  |
| P₄              | 0   | 100  | V₄              | 0.95| 1.1  | T₄              | 0.9 | 1.1  | T₄              | 0.9 | 1.1  | T₄              | 0.9 | 1.1  | T₄              | 0.9 | 1.1  |
| P₅              | 0   | 550  | V₅              | 0.95| 1.1  | T₅              | 0.9 | 1.1  | T₅              | 0.9 | 1.1  | T₅              | 0.9 | 1.1  | T₅              | 0.9 | 1.1  |
| P₆              | 0   | 100  | V₆              | 0.95| 1.1  | T₆              | 0.9 | 1.1  | T₆              | 0.9 | 1.1  | T₆              | 0.9 | 1.1  | T₆              | 0.9 | 1.1  |
| P₇              | 0   | 410  | V₇              | 0.95| 1.1  | T₇              | 0.9 | 1.1  | T₇              | 0.9 | 1.1  | T₇              | 0.9 | 1.1  | T₇              | 0.9 | 1.1  |

Control variables and their ranges (IEEE 30-bus network)
### Table 5. Comparative study of BSA with other algorithm for IEEE 30-bus network

| Simulation set-up | Algorithms | A.P. generation Cost ($/H) | Emission(ton/hr) | Ploss(MW) | Qloss(MW) | VD(p.u) | L-index |
|-------------------|------------|-----------------------------|------------------|-----------|-----------|---------|---------|
| **Simulation set-up (1)** | BSA | 799.7221 | 0.38252 | 9.05 | 32.216 | 0.9029 | 0.1316 |
| | GA | 800.4312 | 0.36112 | 9.02 | 38.102 | 0.9034 | 0.1423 |
| | MSA | 800.5099 | 0.36645 | 9.0345 | 39.614 | 0.90357 | 0.13833 |
| | MPSO | 800.5164 | 0.36624 | 9.0354 | 38.5749 | 0.90488 | 0.13825 |
| | MDE | 800.8399 | 0.3559 | 8.8365 | 39.2789 | 0.77621 | 0.14141 |
| | MFO | 800.6863 | 0.36849 | 9.1492 | 43.8331 | 0.75768 | 0.13914 |
| | FPA | 802.7983 | 0.35959 | 9.5406 | 44.942 | 0.36788 | 0.14908 |
| **Simulation set-up (2)** | BSA | 929.3449 | 0.334919 | 8.11 | 60 | 0.7288 | 0.1543 |
| | GA | 930.6211 | 0.394613 | 11.24 | 61.225 | 0.7319 | 0.154 |
| | MSA | 930.7441 | 0.43493 | 13.1378 | 62.4263 | 0.44929 | 0.15676 |
| | MPSO | 952.3039 | 0.30123 | 7.3049 | 30.9224 | 0.72294 | 0.14028 |
| | MDE | 930.9445 | 0.43333 | 12.7324 | 60.4379 | 0.44702 | 0.15565 |
| | MFO | 930.7189 | 0.4352 | 13.1787 | 63.7446 | 0.46718 | 0.15693 |
| | FPA | 931.7458 | 0.43258 | 12.1073 | 53.4394 | 0.46602 | 0.15071 |
| **Simulation set-up (3)** | BSA | 933 | 0.1909 | 3.21 | 13.54 | 0.8397 | 0.1307 |
| | GA | 940.4122 | 0.20371 | 3.2264 | 20.64 | 0.8522 | 0.1365 |
| | MSA | 944.5003 | 0.20482 | 3.2358 | 22.6688 | 0.87393 | 0.13888 |
| | MPSO | 879.9464 | 0.23246 | 7.0467 | 35.2525 | 0.57387 | 0.14294 |
| | MDE | 927.8066 | 0.20926 | 4.8539 | 23.4377 | 0.39535 | 0.1525 |
| | MFO | 945.4553 | 0.20489 | 3.4295 | 17.8704 | 0.70968 | 0.1393 |
| | FPA | 948.949 | 0.20523 | 4.492 | 23.6465 | 0.42761 | 0.14454 |
| **Simulation set-up (4)** | BSA | 967.4963 | 0.2048 | 3.03 | 15.14 | 0.8017 | 0.1506 |
| | GA | 967.5924 | 0.2066 | 3.1023 | 22.43 | 0.8642 | 0.1671 |
| | MSA | 967.6636 | 0.20727 | 3.1005 | 21.611 | 0.88868 | 0.13858 |
| | MPSO | 967.6523 | 0.20727 | 3.1031 | 17.1822 | 0.90632 | 0.13816 |
| | MDE | 967.6543 | 0.20729 | 3.1619 | 19.1885 | 0.76781 | 0.14055 |
| | MFO | 967.6785 | 0.20727 | 3.1111 | 22.299 | 0.91558 | 0.13815 |
| | FPA | 967.1138 | 0.20756 | 3.5661 | 20.5784 | 0.3893 | 0.14173 |
Table 6. Comparative study of BSA with other various algorithms (IEEE 30-bus network)

| Simulation set-up | A.P generation Cost ($/H) | Emission (ton/H) | A.P loss (MW) | Qloss(MW) | VD(p.u) | L-index |
|-------------------|---------------------------|----------------|---------------|------------|--------|---------|
| Simulation set-up (1): A.P generation cost optimization | | | | | | |
| BSA | 799.7221 | 0.38252 | 9.05 | 32.216 | 0.9029 | 0.1316 |
| GA | 800.4916 | 0.36712 | 9.07 | 38.1322 | 0.90321 | 0.13762 |
| MSA | 800.5099 | 0.36645 | 9.0345 | 39.614 | 0.90357 | 0.13833 |
| RCBBO | 800.8703 | NA | NA | NA | NA | NA |
| ARCBBO | 800.5159 | 0.3663 | 9.0255 | NA | 0.8867 | 0.1385 |
| DE | 801.23 | NA | 9.22 | 38.91 | NA | NA |
| GWO | 801.41 | NA | 9.3 | 38.58 | NA | NA |
| GBICA | 801.1513 | 0.3296 | NA | NA | NA | NA |
| MGBICA | 801.1409 | 0.3296 | NA | NA | NA | NA |
| HSFLA-SA | 801.79 | NA | NA | NA | NA | NA |
| ABC | 800.66 | 0.365141 | 9.0328 | NA | 0.9209 | 0.1381 |
| Simulation set-up (2): Quadratic fuel cost considering valve point loading | | | | | | |
| BSA | 929.3449 | 0.334919 | 8.11 | 60 | 0.7288 | 0.1543 |
| GA | 930.6432 | 0.421165 | 12.44 | 61.2312 | 0.6427 | 0.1554 |
| MSA | 930.7441 | 0.43492 | 13.1358 | 62.4711 | 0.45435 | 0.15691 |
| GABC | 931.745 | NA | 10.957 | NA | 0.4575 | NA |
| ABC | 931.745 | NA | 10.957 | NA | 0.4575 | NA |
| Simulation set-up (3): Emission cost | | | | | | |
| BSA | 933 | 0.1909 | 3.21 | 13.54 | 0.8397 | 0.1307 |
| GA | 942.2764 | 0.20211 | 3.2433 | 19.63 | 0.8722 | 0.1364 |
| MSA | 944.3904 | 0.20482 | 3.2361 | 22.7432 | 0.88059 | 0.1387 |
| ARCBBO | 945.1597 | 0.2048 | 3.2624 | NA | 0.8647 | 0.1387 |
| MGBICA | 942.8401 | 0.2048 | NA | NA | NA | NA |
| GBICA | 944.6516 | 0.2049 | NA | NA | NA | NA |
| DSA | 944.4086 | 0.205826 | 3.24373 | NA | 0.12734 |
| HMPSO-SFLA | 944.4391 | 0.204826 | 3.247 | NA | 0.8463 | 0.1402 |
| ABC | 944.4391 | 0.204826 | 3.247 | NA | 0.8463 | 0.1402 |
| Simulation set-up (4): A.P loss | | | | | | |
| BSA | 967.7963 | 0.2048 | 3.03 | 15.14 | 0.8017 | 0.1506 |
| GA | 969.991 | 0.2099 | 3.453 | 20.67 | 0.87443 | 0.1509 |
| MSA | 967.6636 | 0.20727 | 3.1005 | 21.611 | 0.88868 | 0.13858 |
| ALC-PSO | 967.7683 | NA | 3.17 | NA | NA | NA |
| GWO | 968.38 | NA | 3.41 | 19.43 | NA | NA |
| DSA | 967.6493 | 0.20826 | 3.0945 | NA | 0.12604 |
| ABC | 967.681 | 0.207268 | 3.1078 | NA | 0.9008 | 0.1386 |
| DE | 968.23 | NA | 3.38 | 20.17 | NA | NA |
| EGA | 967.93 | NA | 3.244 | NA | NA | NA |
| EEA | 952.3785 | NA | 3.2823 | NA | NA | NA |
| ARCBBO | 967.6605 | 0.2073 | 3.1009 | NA | 0.8913 | 0.1386 |
## Table 7. Comparison among the control variables of BSA-OPF with MSA-OPF (IEEE 30-bus network)

| Control variables | → | BSA | | MSA | | Algorithms | Simulation set-up | Simulation set-up (1) | Simulation set-up (2) | Simulation set-up (3) | Simulation set-up (4) |
|-------------------|---|-----|-----|-----|-----|--------------|---------------------|----------------------|----------------------|----------------------|
| Pg1               | → | 176.84 | 100.22 | 60.52 | 51.43 | Simulation set-up | 177.213 | 197.569 | 64.997 | 51.501 |
| Pg2               | → | 48.7 | 49.98 | 60.8 | 80 | Simulation set-up (1) | 48.7326 | 51.9685 | 67.639 | 80 |
| Pg5               | → | 22.37 | 12.95 | 50 | 50 | Simulation set-up (2) | 21.4572 | 15.0004 | 50 | 50 |
| Pg8               | → | 20.69 | 10.34 | 35 | 35 | Simulation set-up (3) | 21.0638 | 10 | 35 | 35 |
| Pg11              | → | 11.56 | 11.83 | 30 | 30 | Simulation set-up (4) | 11.9657 | 10 | 30 | 30 |
| Pg13              | → | 12 | 11 | 40 | 40 | Simulation set-up (1) | 12.0021 | 12 | 40 | 40 |
| Vg1               | → | 1.0928 | 1.0565 | 1.1 | 1.1 | Simulation set-up (2) | 1.0848 | 1.03356 | 1.0628 | 1.0619 |
| Vg2               | → | 1.0731 | 1.0325 | 1.0966 | 1.1 | Simulation set-up (3) | 1.0653 | 1.01127 | 1.0564 | 1.0577 |
| Vg5               | → | 1.0345 | 1.0016 | 1.081 | 1.0837 | Simulation set-up (4) | 1.03386 | 0.97135 | 1.0374 | 1.0381 |
| Vg8               | → | 1.0457 | 1.0115 | 1.0868 | 1.0936 | Simulation set-up (1) | 1.03823 | 1.03439 | 1.0436 | 1.0442 |
| Vg11              | → | 1.1 | 1.0951 | 1.1 | 1.1 | Simulation set-up (2) | 1.0927 | 1.09929 | 1.075 | 1.072 |
| Vg13              | → | 1.0966 | 1.1 | 1.1 | 1.0361 | Simulation set-up (3) | 1.04533 | 1.09992 | 1.0534 | 1.0591 |
| TC11              | → | 1.0008 | 0.9222 | 1.0446 | 1.099 | Simulation set-up (4) | 1.04907 | 1.1 | 1.0996 | 1.0907 |
| TC12              | → | 0.9017 | 0.945 | 0.9 | 0.9303 | Simulation set-up (1) | 0.93876 | 1.0532 | 0.9007 | 0.9 |
| TC15              | → | 0.9402 | 0.9446 | 0.969 | 0.9729 | Simulation set-up (2) | 0.97018 | 1.06973 | 0.9969 | 0.9979 |
| TC36              | → | 0.9283 | 0.9172 | 0.9656 | 1.0386 | Simulation set-up (3) | 0.97498 | 1.06513 | 0.9769 | 0.9765 |
| Qc10              | → | 4.66 | 5 | 5 | 5 | Simulation set-up (4) | 2.37123 | 4.98433 | 4.9965 | 5 |
| Qc12              | → | 5 | 5 | 5 | 1.1 | Simulation set-up (1) | 2.57918 | 4.99678 | 4.9978 | 0.7672 |
| Qc15              | → | 4.23 | 5 | 5 | 5 | Simulation set-up (2) | 4.20734 | 4.99345 | 3.3396 | 4.2297 |
| Qc17              | → | 4.98 | 5 | 5 | 2.2 | Simulation set-up (3) | 5 | 4.99414 | 4.999 | 4.999 |
| Qc20              | → | 4.56 | 4.95 | 4.24 | 4.62 | Simulation set-up (4) | 3.68771 | 4.65486 | 4.9998 | 3.9671 |
| Qc21              | → | 5 | 5 | 5 | 1.77 | Simulation set-up (1) | 4.95747 | 4.99686 | 4.9985 | 5 |
| Qc23              | → | 2.13 | 2.71 | 2.75 | 4.35 | Simulation set-up (2) | 3.08148 | 4.99969 | 2.9523 | 3.0134 |
| Qc24              | → | 5 | 5 | 5 | 5 | Simulation set-up (3) | 4.98767 | 4.99499 | 4.998 | 5 |
| Qc29              | → | 1.75 | 2.55 | 2.13 | 5 | Simulation set-up (4) | 2.48706 | 4.995 | 2.2315 | 2.328 |
### Table 8. Statistical representation of and CPU timing of simulation set-up (1)

| Algorithms   | Best      | Average   | Worst      | CPU time (Sec) |
|--------------|-----------|-----------|------------|----------------|
| BSA          | 799.7221  | 799.012   | 799.7411   | 14.22          |
| GA           | 800.4312  | 800.116   | 800.853    | 15.02          |
| MSA          | NA        | NA        | NA         | NA             |
| RCBBO        | 800.8703  | 800.02    | 800.9431   | NA             |
| ARCBBO       | 800.5159  | 800.6412  | 800.9262   | NA             |
| DE           | 801.231   | 801.282   | 801.622    | 16.2           |
| GWO          | 801.413   | 801.655   | 801.958    | 15.8           |
| GBICA        | NA        | NA        | NA         | NA             |
| MGBICA       | NA        | NA        | NA         | NA             |
| HSFLA-SA     | NA        | NA        | NA         | 18.93          |
| ABC          | 800.66    | 800.02    | 800.9431   | NA             |
| Simulation set-up | Algorithms | Total Cost ($/H) | A.P generation Cost ($/H) | Emission | A.Ploss | Qloss | VD (p.u) | L-index |
|-------------------|------------|------------------|---------------------------|-----------|---------|-------|---------|---------|
| Simulation set-up (5) | BSA | 1031.194 | 857.994 | 0.205675 | 4.33 | 20.49 | 0.8799 | 0.1537 |
| GA | 1033.246 | 858.765 | 0.21564 | 4.4803 | 21.8766 | 0.91362 | 0.15421 |
| MSA | 1040.808 | 859.1915 | 0.22899 | 4.5404 | 21.9075 | 0.92852 | 0.13814 |
| MPSO | 1041.221 | 859.5841 | 0.2287 | 4.5409 | 22.3987 | 0.94718 | 0.13775 |
| MDE | 1044.054 | 868.7138 | 0.22525 | 4.3891 | 24.2043 | 0.87816 | 0.13787 |
| MFO | 1041.671 | 858.5812 | 0.22947 | 4.5772 | 23.8781 | 0.89944 | 0.13806 |
| FPA | 1055.719 | 855.2706 | 0.22959 | 4.7981 | 24.5207 | 1.0143 | 0.13811 |
| Simulation set-up (6) | BSA | 805.0619 | 803.7 | 0.274806 | 9.604 | 35.11 | 0.10569 | 0.1451 |
| GA | 811.9432 | 803.991 | 0.394102 | 9.71243 | 42.553 | 0.10436 | 0.14694 |
| MSA | 814.1545 | 803.3125 | 0.36344 | 9.7206 | 42.6646 | 0.10842 | 0.14783 |
| MPSO | 815.9983 | 803.9787 | 0.3636 | 9.9242 | 42.2652 | 0.1202 | 0.14903 |
| MDE | 815.8582 | 803.2122 | 0.36218 | 9.5974 | 40.867 | 0.12646 | 0.14943 |
| MFO | 814.3541 | 803.7911 | 0.36355 | 9.8685 | 50.6485 | 0.10563 | 0.14906 |
| FPA | 817.3228 | 803.6638 | 0.36803 | 9.9252 | 45.574 | 0.13659 | 0.14751 |
| Simulation set-up (7) | BSA | 814.0645 | 799.43 | 0.344806 | 8.882 | 38.16 | 0.9055 | 0.1312 |
| GA | 814.90443 | 800.553 | 0.35603 | 8.9442 | 39.447 | 0.91652 | 0.13661 |
| MSA | 814.9378 | 801.2248 | 0.36106 | 8.9761 | 40.243 | 0.92655 | 0.13713 |
| MPSO | 815.4446 | 801.6966 | 0.36194 | 9.2003 | 37.9253 | 0.83012 | 0.13748 |
| MDE | 815.8431 | 802.0991 | 0.35484 | 9.0613 | 37.2564 | 0.88754 | 0.13744 |
| MFO | 815.427 | 801.668 | 0.34299 | 8.5578 | 35.6815 | 0.83817 | 0.13759 |
| FPA | 814.9067 | 801.1487 | 0.3718 | 9.3174 | 39.4019 | 0.87563 | 0.13758 |
| Simulation set-up (8) | BSA | 852.1012 | 830.597 | 0.2423 | 5.6 | 27.36 | 0.1813 | 0.1472 |
| GA | 960.2351 | 830.604 | 0.2533 | 5.6102 | 27.3721 | 0.2874 | 0.1483 |
| MSA | 965.2905 | 830.639 | 0.25258 | 5.6219 | 27.2774 | 0.29385 | 0.14802 |
| MPSO | 986.0063 | 833.6807 | 0.25251 | 6.5245 | 29.1151 | 0.18991 | 0.14746 |
| MDE | 973.6116 | 829.0942 | 0.2575 | 6.0569 | 28.4491 | 0.30347 | 0.14872 |
| MFO | 965.8077 | 830.9135 | 0.25231 | 5.5971 | 27.2355 | 0.33164 | 0.14556 |
| FPA | 971.9076 | 835.3699 | 0.24781 | 5.5153 | 26.6517 | 0.49969 | 0.14873 |
### Table 10. Relative analysis among the control variables of BSA and MSA (IEEE 30-bus network)

| Control variables | Algorithms | BSA | MSA |
|-------------------|------------|-----|-----|
|                   | Simulation set-up(5) | Simulation set-up(6) | Simulation set-up(7) | Simulation set-up(8) | Simulation set-up(5) | Simulation set-up(6) | Simulation set-up(7) | Simulation set-up(8) |
| $P_{G1}$          | 102.17     | 177.42 | 172.61 | 121.82 | 102.8129 | 176.2053 | 175.6415 | 121.9858 |
| $P_{G2}$          | 55.73      | 48.02  | 53.66  | 50.49  | 55.0797 | 48.7218 | 47.0661 | 52.5624 |
| $P_{G3}$          | 37.58      | 21.70  | 20.04  | 31.51  | 38.2097 | 21.8452 | 21.5451 | 31.5466 |
| $P_{G4}$          | 35.0       | 21.12  | 23.91  | 33.01  | 34.9995 | 22.2104 | 21.0438 | 34.9913 |
| $P_{G5}$          | 30.0       | 13.02  | 10     | 28.09  | 29.9947 | 12.1357 | 14.7626 | 26.5086 |
| $P_{G6}$          | 27.25      | 12.00  | 12     | 22.07  | 26.8439 | 12.0022 | 12.317  | 21.4272 |
| $V_{G1}$          | 1.0837     | 1.0307 | 1.0994 | 1.0701 | 1.06944 | 1.05052 | 1.07742 | 1.07067 |
| $V_{G2}$          | 1.0752     | 1.0193 | 1.0737 | 1.0580 | 1.05856 | 1.0313  | 1.0616  | 1.05748 |
| $V_{G3}$          | 1.0546     | 1.0059 | 1.0313 | 1.030  | 1.0346  | 1.01057 | 1.0331  | 1.03024 |
| $V_{G4}$          | 1.0663     | 1.0002 | 1.0522 | 1.039  | 1.04288 | 1.00766 | 1.04836 | 1.03906 |
| $V_{G5}$          | 1.1        | 1.0132 | 1.1    | 1.009  | 1.08952 | 1.02101 | 1.0999  | 1.00917 |
| $V_{G6}$          | 1.1        | 1.0635 | 1.0803 | 1.039  | 1.05493 | 0.992125 | 1.05084 | 1.03987 |
| $T_{G1}$          | 1.0303     | 1.0157 | 0.9315 | 1.056  | 1.024   | 1.03943 | 1.04275 | 1.0558  |
| $T_{G2}$          | 0.9000     | 0.9000 | 1.1    | 0.9394 | 0.962817 | 0.900965 | 0.90553 | 0.939783 |
| $T_{G3}$          | 0.9709     | 1.0470 | 1.0398 | 1.0710 | 0.98958 | 0.933765 | 0.974468 | 1.06393 |
| $T_{G4}$          | 0.9637     | 0.9593 | 0.9518 | 1.004  | 0.976004 | 0.956971 | 0.971978 | 1.00596 |
| $Q_{C10}$         | 2.96       | 0.46   | 5.0    | 2.22   | 1.98213 | 5       | 3.38991 | 2.22721 |
| $Q_{C12}$         | 5.0        | 0.28   | 2.2    | 1.99   | 1.68599 | 2.2444  | 1.83146 | 1.99685 |
| $Q_{C13}$         | 5.0        | 0.30   | 5.0    | 4.53   | 4.18104 | 4.75979 | 2.98534 | 4.45733 |
| $Q_{C15}$         | 5.0        | 0.30   | 5.0    | 2.61   | 5       | 0.271973 | 1.09045 | 2.51507 |
| $Q_{C16}$         | 4.48       | 5.0    | 5      | 3.94   | 3.62953 | 4.99208 | 0.673286 | 3.93636 |
| $Q_{C17}$         | 5.0        | 5.0    | 3.63   | 4.96   | 4.95832 | 4.9143  | 3.74157 | 4.99047 |
| $Q_{C18}$         | 2.74       | 4.11   | 5      | 5.12   | 2.88178 | 4.82359 | 2.45557 | 4.32656 |
| $Q_{C19}$         | 5.0        | 4.99   | 0      | 4.88   | 4.99866 | 4.93992 | 2.34699 | 4.96993 |
| $Q_{C20}$         | 3.07       | 1.75   | 3.32   | 3.21   | 2.59549 | 0.955192 | 2.38303 | 3.17221 |
Table 11. Description of IEEE 57-bus network

| Feature                              | Quantity | Description                                                                 |
|--------------------------------------|----------|-----------------------------------------------------------------------------|
| Buses                                | 57       | (Zimmerman and Sanchez, 2015)                                               |
| Branches                             | 80       | (Zimmerman and Sanchez, 2015)                                               |
| Generators                           | 7        | Buses- 1, 2, 3, 6, 8, and 12.                                               |
| Parallel Reactive Compensator        | 3        | Buses- 18, 25 and 53.                                                       |
| Tap setting of regulating Transformer| 17       | Branches- 19, 20, 31, 35, 36, 37, 41, 46, 54, 58, 59, 65, 66, 71, 73, 76 and 80. |
| Control variables                    | 33       | —                                                                           |

Table 12. Control variables and their ranges (IEEE 57-bus network)

| Control variables | Min  | Max  | Control variables | Min  | Max  | Control variables | Min  | Max  | Control variables | Min  | Max  | Control variables | Min  | Max  |
|-------------------|------|------|-------------------|------|------|-------------------|------|------|-------------------|------|------|-------------------|------|------|
| P_{g1}            | 50   | 200  | V1                | 0.95 | 1.1  | T_{11}            | 0.9  | 1.1  | Q_{15}            | 0    | 5    | Q_{23}            | 0    | 5    |
| P_{g2}            | 20   | 80   | V2                | 0.95 | 1.1  | T_{12}            | 0.9  | 1.1  | Q_{17}            | 0    | 5    |                   |      |      |
| P_{g5}            | 15   | 50   | V5                | 0.95 | 1.1  | T_{15}            | 0.9  | 1.1  | Q_{20}            | 0    | 5    |                   |      |      |
| P_{g8}            | 10   | 35   | V8                | 0.95 | 1.1  | T_{26}            | 0.9  | 1.1  | Q_{23}            | 0    | 5    |                   |      |      |
| P_{g11}           | 10   | 30   | V11               | 0.95 | 1.1  | Q_{38}            | 0    | 5    | Q_{23}            | 0    | 5    |                   |      |      |
| P_{g13}           | 12   | 40   | V13               | 0.95 | 1.1  | Q_{42}            | 0    | 5    | Q_{24}            | 0    | 5    |                   |      |      |
Table 13. Comparative study of BSA with other algorithms for IEEE 57- bus network

| Simulation set-up | Algorithms | A.P generation Cost ($/h) | Emission(ton/h) | A.P loss(MW) | Qloss(MW) | VD(p.u) | L-index |
|-------------------|------------|---------------------------|----------------|--------------|-----------|---------|---------|
| Simulation set-up (9) | BSA        | 41622                     | 1.9022         | 12.04        | 64.52     | 1.50859 | 0.1901  |
|                    | GA         | 41629.93                  | 1.9237         | 14.433       | 66.7412   | 1.54331 | 0.26442 |
|                    | MSA        | 41673.72                  | 1.9526         | 15.0526      | 67.8569   | 1.5508  | 0.28392 |
|                    | MPSO       | 41678.68                  | 1.9443         | 15.1271      | 68.2332   | 1.3397  | 0.28872 |
|                    | MDE        | 41695.81                  | 2.0291         | 15.9052      | 71.3467   | 1.2101  | 0.29232 |
|                    | MFS        | 41686.41                  | 2.0036         | 15.611       | 70.2146   | 1.2938  | 0.29017 |
|                    | FPA        | 41701.96                  | 2.0688         | 16.1543      | 71.4409   | 1.2818  | 0.29183 |
| Simulation set-up (10) | BSA        | 41675                     | 1.449          | 15.58        | 72.189    | 0.58055 | 0.2202  |
|                    | GA         | 41701.65                  | 1.7453         | 15.7552      | 74.116    | 0.64328 | 0.27546 |
|                    | MSA        | 41714.99                  | 1.9551         | 15.9214      | 75.2315   | 0.67818 | 0.29533 |
|                    | MPSO       | 41721.61                  | 2.0096         | 16.2453      | 76.4918   | 0.67813 | 0.2955  |
|                    | MDE        | 41717.39                  | 1.9888         | 16.0961      | 76.0831   | 0.6781  | 0.2952  |
|                    | MFO        | 41718.87                  | 2.0149         | 16.2189      | 76.5491   | 0.67796 | 0.29525 |
|                    | FPA        | 41726.38                  | 1.9213         | 16.027       | 74.6402   | 0.69723 | 0.29488 |
| Simulation set-up (11) | BSA        | 41674                     | 1.7184         | 13.41        | 58.652    | 1.23824 | 0.2223  |
|                    | GA         | 41675.08                  | 1.8213         | 14.662       | 65.0453   | 1.6226  | 0.26311 |
|                    | MSA        | 41675.99                  | 1.9188         | 15.0026      | 67.0164   | 1.7236  | 0.27481 |
|                    | MPSO       | 41694.14                  | 1.977          | 15.4554      | 68.6211   | 1.5084  | 0.27918 |
|                    | MDE        | 41689.59                  | 2              | 15.7092      | 70.6257   | 1.5447  | 0.27677 |
|                    | MFO        | 41680.19                  | 1.9192         | 15.1026      | 67.2447   | 1.7245  | 0.27467 |
|                    | FPA        | 41684.19                  | 1.9223         | 15.2193      | 67.7491   | 1.7478  | 0.27429 |
Table 14. Control variables of BSA-OPF and MSA-OPF (IEEE 57-bus network)

| Control variables | Algorithms → Algorithms→ | BSA | MSA | MSA | MSA |
|-------------------|--------------------------|-----|-----|-----|-----|
|                   | Simulation set-up        | Simulation set-up(9) | Simulation set-up(10) | Simulation set-up(11) | Simulation set-up(9) | Simulation set-up(10) | Simulation set-up(11) |
| $P_{g1}$          | →                        | 140.14 | 141.87 | 141.01 | 143.3899 | 143.8661 | 142.5634 |
| $P_{g2}$          | →                        | 95.46 | 74.45 | 70.05 | 90.0784 | 85.34818 | 94.7494 |
| $P_{g3}$          | →                        | 42.87 | 42.63 | 45.04 | 45.186 | 45.85493 | 45.2793 |
| $P_{g4}$          | →                        | 73.05 | 72.1 | 71.01 | 68.98911 | 71.30797 | 65.031 |
| $P_{g5}$          | →                        | 461.64 | 478.25 | 460.5 | 462.8671 | 462.4092 | 460.104 |
| $P_{g6}$          | →                        | 94.83 | 86.12 | 94.12 | 94.13925 | 94.08068 | 97.8619 |
| $P_{g7}$          | →                        | 357.33 | 370.96 | 379.6 | 361.2028 | 363.8543 | 360.214 |
| $V_{g1}$          | →                        | 1.0455 | 1.0443 | 1.0433 | 1.065677 | 1.022121 | 1.06941 |
| $V_{g2}$          | →                        | 1.0504 | 1.0467 | 1.0457 | 1.063393 | 1.019646 | 1.06744 |
| $V_{g3}$          | →                        | 1.0437 | 1.031 | 1.032 | 1.055744 | 1.013444 | 1.05959 |
| $V_{g4}$          | →                        | 1.0633 | 1.0488 | 1.0458 | 1.059543 | 1.025691 | 1.06239 |
| $V_{g5}$          | →                        | 1.0849 | 1.0558 | 1.0568 | 1.071391 | 1.044968 | 1.07655 |
| $V_{g6}$          | →                        | 1.067 | 1.0462 | 1.0442 | 1.047925 | 1.014033 | 1.05323 |
| $V_{g7}$          | →                        | 1.0464 | 1.0259 | 1.0269 | 1.050537 | 1.010858 | 1.05804 |
| $T_{c19}$         | →                        | 0.9095 | 0.973 | 0.983 | 1.003475 | 0.910173 | 0.97996 |
| $T_{c20}$         | →                        | 0.9007 | 1.0206 | 1.026 | 1.008993 | 1.075124 | 1.04299 |
| $T_{c31}$         | →                        | 0.9975 | 1.0479 | 1.0478 | 0.983895 | 0.985418 | 1.03299 |
| $T_{c35}$         | →                        | 0.9019 | 0.948 | 0.958 | 1.007633 | 0.987232 | 0.95576 |
| $T_{c36}$         | →                        | 0.9089 | 0.9789 | 0.9799 | 1.015505 | 1.053424 | 1.021 |
| $T_{c37}$         | →                        | 0.9772 | 0.929 | 0.939 | 0.998161 | 1.016568 | 1.02878 |
| $T_{c41}$         | →                        | 0.9 | 0.9022 | 0.9032 | 0.998831 | 1.00709 | 0.99282 |
| $T_{c46}$         | →                        | 0.9 | 0.9901 | 0.9191 | 0.943436 | 0.934802 | 0.90414 |
| $T_{c44}$         | →                        | 0.9134 | 0.9526 | 0.9546 | 0.919784 | 0.900021 | 0.98236 |
| $T_{c48}$         | →                        | 0.9014 | 0.9549 | 0.9539 | 0.993043 | 0.947947 | 0.98234 |
| $T_{c49}$         | →                        | 0.9 | 0.9533 | 0.9523 | 0.98933 | 0.960869 | 0.96929 |
| $T_{c55}$         | →                        | 0.9131 | 0.9496 | 0.9498 | 0.988909 | 0.978141 | 0.97835 |
| $T_{c56}$         | →                        | 0.9 | 0.9469 | 0.9460 | 0.954368 | 0.918285 | 0.95643 |
| $T_{c71}$         | →                        | 0.9029 | 0.9464 | 0.9465 | 0.973045 | 0.950935 | 0.96617 |
| $T_{c73}$         | →                        | 1.0263 | 1.0053 | 1.0053 | 0.965965 | 0.994123 | 1.01585 |
| $T_{c76}$         | →                        | 0.9927 | 1.0415 | 1.0416 | 0.920549 | 0.936163 | 1.03695 |
| $Q_{c18}$         | →                        | 0.9013 | 0.906 | 0.916 | 0.997742 | 0.998129 | 1.01122 |
| $Q_{c25}$         | →                        | 0.0637 | 0.1128 | 0.1128 | 15.40877 | 11.88253 | 17.6121 |
| $Q_{c33}$         | →                        | 0.0972 | 0.175 | 0.165 | 16.56182 | 16.78665 | 8.38107 |
| $Q_{c33}$         | →                        | 0.1785 | 0.0747 | 0.0746 | 16.40806 | 18.28455 | 8.79627 |
### Table 15. Comparative representation of cost between different algorithms (IEEE 57-bus network)

| Algorithms | A.P generation Cost ($/h) | CPU time (Sec) |
|------------|---------------------------|----------------|
| BSA        | 41622                     | 38.331         |
| GA         | 41629.93                  | 42.66          |
| MSA        | 41673.72                  | NA             |
| MO-DEA     | 41683                     | NA             |
| DSA        | 41686.82                  | NA             |
| ARCBBO     | 41686                     | NA             |
| MGBICA     | 41715.71                  | NA             |
| ABC        | 41693.96                  | NA             |
| MICA–TLA   | 41675.05                  | 44.56          |
| IEM        | 4810.216                  | NA             |

### Table 16. Description of IEEE 118-bus network

| Features                              | Quantity | Description |
|---------------------------------------|----------|-------------|
| Buses                                 | 118      | (Zimmerman and Sanchez, 2015) |
| Branches                              | 186      | (Zimmerman and Sanchez, 2015) |
| Generators                            | 54       | Buses: 1, 4, 6, 8, 10, 12, 15, 18, 19, 24, 25, 26, 27, 31, 32, 34, 36, 40, 42, 46, 49, 54, 55, 56, 59, 61, 62, 65, 66, 69, 70, 72, 73, 74, 76, 77, 80, 85, 87, 89, 90, 91, 92, 99, 100, 103, 104, 105, 107, 110, 111, 112, 113 and 116. |
| Parallel Reactive Compensator         | 14       | Buses-5, 34, 37, 44, 45, 46, 48, 74, 79, 82, 83, 105, 107 and 110. |
| Tap setting of regulating Transformer | 9        | Branches-8, 32, 36, 51, 93, 95, 102, 107 and 127. |
| Control variables                     | 130      |             |

### Table 17. Different objective functions as obtained by BSA and some other algorithms for the IEEE 118-bus network

| Simulation set-up | Algorithms | A.P generation Cost ($/h) | A.Ploss (MW) | Qloss (MW) | VD (p.u) | L-index |
|-------------------|------------|---------------------------|--------------|------------|----------|---------|
| Simulation set-up (9) | BSA        | **129620.0**              | 76.6         | 456.536    | 1.085    | 0.01    |
|                    | MSA        | 129640.7                  | 73.2601      | 460.8088   | 3.0728   | 0.061467|
|                    | MPSO       | 132039.2                  | 112.8486     | 718.2268   | 1.1545   | 0.068919|
|                    | MDE        | 130444.6                  | 71.6383      | 451.8952   | 1.3146   | 0.066577|
|                    | MFO        | 129708.1                  | 74.7063      | 469.639    | 2.3761   | 0.062172|
|                    | FPA        | 129688.7                  | 74.3242      | 467.4772   | 2.5391   | 0.061775|
Table 18. Cost comparison of BSA with other algorithms for IEEE 118-bus network

| Algorithms | A.P generation cost ($/h) |
|------------|----------------------------|
| BSA        | 129620                     |
| MSA        | 129640.7                   |
| PSOGSA     | 129733.58                  |
| DSA        | 129691.6                   |
| FHSAs      | 132138.3                   |
| HSA        | 132319.6                   |
| ICBO       | 135121.6                   |
| TLBO       | 129682.8                   |
| Control variables | BSA | MSA | Control variables | BSA | MSA | Control variables | BSA | MSA | Control variables | BSA | MSA |
|------------------|-----|-----|------------------|-----|-----|------------------|-----|-----|------------------|-----|-----|
| **Simulation set-up (12)** | | | | | | | | | | | |
| Pg4 | 0.608 | 0.741997 | | | | | | | | | |
| Pg6 | 2.29 | 2.33579 | | | | | | | | | |
| Pg8 | 0.64 | 0.766761 | | | | | | | | | |
| Pg10 | 380.9 | 394.8925 | | | | | | | | | |
| Pg12 | 71.60 | 85.69232 | | | | | | | | | |
| Pg14 | 16.52 | 17.62044 | | | | | | | | | |
| Pg16 | 22.80 | 33.77219 | | | | | | | | | |
| Pg18 | 30.11 | 32.41324 | | | | | | | | | |
| Pg20 | 0.37 | 0.411386 | | | | | | | | | |
| Pg22 | 189.79 | 190.7811 | | | | | | | | | |
| Pg24 | 230.55 | 273.6254 | | | | | | | | | |
| Pg26 | 19.50 | 19.47055 | | | | | | | | | |
| Pg28 | 7.137 | 7.337286 | | | | | | | | | |
| Pg30 | 26.47 | 28.63474 | | | | | | | | | |
| Pg32 | 11.08 | 11.09593 | | | | | | | | | |
| Pg34 | 3.420 | 4.285056 | | | | | | | | | |
| Pg36 | 3.285 | 3.95023 | | | | | | | | | |
| Pg38 | 31.310 | 31.31559 | | | | | | | | | |
| Pg40 | 16.150 | 19.51715 | | | | | | | | | |
| Pg42 | 190.32 | 190.5231 | | | | | | | | | |
| Pg44 | 48.82 | 48.88164 | | | | | | | | | |
| Pg46 | 36.91 | 36.84914 | | | | | | | | | |
| Pg48 | 56.010 | 56.40172 | | | | | | | | | |
| Pg50 | 146.102 | 146.1092 | | | | | | | | | |
| Pg52 | 144.270 | 144.481 | | | | | | | | | |
| Pg54 | 0 | 0 | | | | | | | | | |
| Pg56 | 347.30 | 347.2867 | | | | | | | | | |
| Pg58 | 344.806 | 344.9046 | | | | | | | | | |
| Pg60 | 663.60 | 663.6643 | | | | | | | | | |
| Pg62 | 3.680 | 3.687839 | | | | | | | | | |
| Pg64 | 100 | 100 | | | | | | | | | |
| Pg66 | 90.32 | 90.51219 | | | | | | | | | |
| Pg68 | 96.08 | 9.182879 | | | | | | | | | |
| Pg70 | 100 | 100 | | | | | | | | | |
| Pg72 | 96.18 | 96.18579 | | | | | | | | | |
| Pg74 | 86.81 | 423.524 | | | | | | | | | |
| Pg76 | 98.45 | 98.35756 | | | | | | | | | |
| Pg78 | 100 | 100 | | | | | | | | | |
| Pg80 | 68.1 | 423.527 | | | | | | | | | |
| Pg82 | 100 | 100 | | | | | | | | | |
| Pg84 | 74.32 | 2.061865 | | | | | | | | | |
| Pg86 | 97.12 | 2.893292 | | | | | | | | | |
| Pg88 | 100 | 100 | | | | | | | | | |
| Pg90 | 100 | 100 | | | | | | | | | |
| Pg92 | 100 | 100 | | | | | | | | | |
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