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Allocation of distributed generation and battery switching stations for electric vehicle using whale optimiser algorithm

*U. Sultana, **Azhar B. Khairuddin, ***Nadia Rasheed, ****Sajid Hussain Qazi, and **A.S.Mokhtar

**Department of Electrical Engineering, NED University of Engineering and Technology, Karachi, Pakistan.*

***School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.*

****University College of Engineering & Technology (UCE&T), The Islamia University of Bahawalpur (IUB), 63100, Bahawalpur, Pakistan*

*****Department of Electrical Engineering, Mehran UET, SZAB Campus, Khairpur Mir's. Pakistan.*

**Corresponding Author: siqara@yahoo.com*

ABSTRACT

With the increasing demand for electrical vehicles (EVs) in the existing distribution system due to road traffic sustainability, fuel costs reduction, and environmental improvement by the promotion of low carbons in transportation, system planners need to minimise energy losses and improve voltage profile of the grid. Few studies resolved these issues via optimum placement of distributed generation (DG) and battery switching station (BSS) units in distribution system; however, these techniques considered only active power loss minimisation with various methodological limitations. Therefore, a new application of whale optimiser algorithm (WOA) is proposed to solve these limitations. The simultaneous placement based approach of the units has been adopted to minimise active and reactive energy losses of 33- and 69-bus distribution systems. System performance has been analyzed based on multiple technical criteria, such as system loading factor, voltage profile improvement, and active and reactive power loss reduction indices. The results of WOA have been proven to be superior to those of artificial bee colony and gravitational search algorithms. Therefore, the proposed methodology can guide energy planners in determining optimal allocation of multiple DG and BSS units in their systems,; in addition to the expected energy loss reduction within the system, BSS, and DG planning and operational constraints.

Keywords: Battery switching stations; distributed generation; electric vehicle; energy losses; whale optimiser algorithm.

NOMENCLATURE

$\left\lvert AE_{system}^{loss}\right\rvert_{DG-BSS}$	Active energy loss of system with DG and BSS units	P_{bi}^{loss}	Real power loss of ith distribution lines
$\left\lvert AE_{system}^{loss}\right\rvert_{w/oDG-BSS}$	Active energy loss of network without DG and BSS units	$P_{K}^{DG,\max}$	Maximum real power of kth DG
$\left\lvert RE_{system}^{loss}\right\rvert_{DG-BSS}$	Reactive energy loss of system with DG and BSS units	$P_{K}^{DG,new}$	New real power of kth DG
$\left\lvert RE_{system}^{loss}\right\rvert_{w/oDG-BSS}$	Reactive energy loss of network without DG and BSS units	$P_{total}^{DG,\max}$	Maximum limit of total active power of DG in the system
$P_{system}^{loss}\Big\rvert_{DG-BSS}$	Real power loss in the system with DG and BSS units	$p.f_{DG}$	Power factor of DG
$P_{system}^{loss}\Big\rvert_{w/oDG-BSS}$	Active power loss in the system without DG and BSS units	$P_{K}^{DG,\min}$	Minimum real power of kth DG
$Q_{system}^{loss}\Big\rvert_{DG-BSS}$	Reactive power loss in the system with DG and BSS units	$V_{j,new}^{bus}$	Voltage at jth bus after DG and BSS allocation
$Q_{system}^{loss}\Big\rvert_{w/oDG-BSS}$	Reactive power loss in the system without DG and BSS units	Q_{bi}^{loss}	Imaginary power loss of ith distribution lines
$\left\lvert LF_{system}^{\max}\right\rvert_{w/oDG-BSS}$	Maximum values of the loading factor of system without considering DG and BSS units	P_{unit}^{BSS}	Active power demand of BSS units
$\left\lvert LF_{system}^{\max}\right\rvert_{DG-BSS}$	Maximum values of the loading factor of system considering DG and BSS units	P_{ChS}^{BSS}	Active power demand of each charging slot
$\left\lvert load_{j}^{bus}\right\rvert_{w/oDG-BSS}$	Demand (pu) at jth bus in the absence of DG and BSS unit	$I_{bi}^{\max}$	Maximum allowable ith branch current
$\left\lvert load_{j}^{bus}\right\rvert_{DG-BSS}$	Demand (pu) at Kth bus in the presence of DG and BSS unit	I_{bi}^{DG-BSS}	Current of ith branch in the presence of DG and BSS
Q_{DG}^{k}	Reactive power of Kth DG	P_{DG}^{k}	Active power of Kth DG
$Q_{K}^{DG,new}$	New reactive power of kth DG	P_{j}^{load}	Active power demand on jth bus
$\left\lvert V_{j}^{bus}\right\rvert_{w/oDG-BSS}$	Voltage level without DG and BSS units at jth bus in pu	Q_{j}^{load}	Reactive power demand on jth bus
$\left\lvert V_{j}^{bus}\right\rvert_{DG-BSS}$	Voltage level with DG and BSS units at jth bus in pu	$P_{substation}$	Active power of substation
$I_{bi}^{w/oDG-BSS}$	The ith branch current in the absence of DG and BSS unit	$Q_{substation}$	Reactive power of substation
I_{bi}^{DG-BSS}	The ith branch current in the presence of DG and BSS unit	N_{bus}	Total number of buses of the system

INTRODUCTION

EVs have been a central focus due to their enhancements in road traffic sustainability as well as being environmentally friendly by the promotion of low carbons in transportation (Liu *et al.*, 2016). Policies and standards have been enacted by U.SA., Japan, European countries, and many others, for the support in the development of EVs and their related facilities (Liu *et al.*, 2016). Electric Power and Research Institute (EPRI) stated that the electricity demand due to plug-in hybrid EVs would be expected to increase by 282 MMWh (Million Megawatt Hours) and 598 MMWh in 2030 and 2050, respectively (2007). From 2013 through 2040, the consumption of electricity in residential, commercial, industrial, and transport sectors is projected to, respectively, an increase by 0.5%, 0.8%, 0.9%, and 3.4% annually, based on U.S. Energy Information Administration (EIA) report (2015, Sultana *et al*., 2016a). The power requirement is increasing in the highest manner as the demand for other sectors. The tremendous growth of electricity demand has consequently increased the adverse effects on the systems performance. In other words, the integration of EVs charging components with distribution network has caused an increase in power losses, reduced system stability, and increased undesirable voltage drops (Jamian *et al*., 2014b, Masoum et al., 2011). As reported in (Kalambe and Agnihotri, 2014), distribution companies are economically penalized if active power losses of the distribution systems are high compared to standard losses, or if, in contrast, they make outrageous profits. In addition, these losses can reduce the efficiency of transmitting energy to the customer (Sultana *et al*., 2016b)., On the other hand, a reduction in imaginary power losses enhances the loadability of the system, improves the bus voltage magnitude, supports the flow of real power through branches, and suspends system up-gradation (Ramesh *et al*., 2008, Hung and Mithulananthan, 2014). Therefore, active and reactive power loss reduction will provide substantial benefits to the distribution system.

On the other side, the battery charging mode has been the main mode of energy supply to EVs recently, since it is easy to set up and has lower one time investment (Liu *et al*., 2016). According to the Society of Automotive Engineers (SAE), Level 1, Level 2, and Level 3 are the main classes of EV charging stations (Wencong *et al*., 2012). Level 1 and Level 2 charging stations follow the normal charging mode, while Level 3 follows fast charging scheme in the charging station. Attention of researchers is recently focused on optimal planning of rapid/fast charging stations or EVs charging stations (ISLAM *et al*., 2016, Liu *et al*., 2013, Sadeghi-Barzani *et al*., 2014). However, multiple problems may occur in the distribution network due to the fast DC charging mode, such as inflicting higher stress on distribution transformers, high harmonic losses, voltage distortion, and reduction in the lifetime of the transformer (Jamian *et al*., 2014b). In addition, increasing the charging capacity of EV may hit the loading limit of certain line segments in distribution networks; it may also cause the voltage to drop at certain nodes (Chen *et al*., 2011). The Level 1 and Level 2 charging stations exert less impact on the distribution system than Level 3 charging stations (Jamian *et al*., 2014b). However, both types of charging units need a long time to charge their batteries (Jamian *et al*., 2014b).

A novel mobility system, namely, battery switching station (BSS), is introduced by two recently established firms, Tesla Motors and Better Place (Avci *et al*., 2014). This system combines a BSS network and a payment platform, owned by companies, allowing users to be charged per mile. Therefore, the battery charging time issue is resolved by this novel mobility system because the depleted battery is replaced by fully charged battery in around 90 seconds or less (Avci *et al*., 2014). The range anxiety and cost of battery issues have been addressed through this system. In addition, the peak demand for the grid can be avoided by battery swapping, possibly saving a significant amount in the running cost (Shareef *et al*., 2016). Having carried out comparative studies, BSS is found to be more realistic and efficient compared to plug-in charging stations in distribution power networks for public transportations (Pan and Zhang, 2016). So, battery charging stations have been rapidly developed for energizing EVs belonging to the battery charging mode (Liu *et al*., 2016). Recently, a strategic agreement was signed between the companies, BAIC Beijing Electric Vehicle (BAIC BJEV) and Sinopec' Beijing Oil in July 2015, to build swapping services for EVs, based on the gas station network (Liu *et al*., 2016). In this research, Level 2 switching stations have been adapted for energizing the batteries for EVs. This is due to its noteworthy benefits for customer and the utility, and its capability of reducing the impact of charging component on the grid.

Due to unavoidable advantages, BSS network has provided a promising solution to handle the limitations of EVs adoptions against fuel based vehicles. However, the influence of inappropriate placement of BSS units on the distribution system is enormous (Jamian *et al*., 2014b). Researchers are proposing multiple innovative solutions for placement of BSS. Liu et al. proposed a new method for planning the sites and sizes of BSS for EVs, considering the demand side management (Liu *et al*., 2016). Using the method of hierarchical clustering optimised allocation of battery EV recharging stations was achieved for urban areas (Ip *et al*., 2010). In addition, the authors proposed a framework for the lifecycle cost for the optimal planning of BSS (Zheng *et al*., 2014).

On the other hand, the distributed generation (DG) is playing a key role with the distribution network operators (DNOs) in the distribution market to meet the demand of electricity consumers without compromising the system's efficiency. Therefore, using conventional, optimization and hybrid approaches, the system's technical, economic and environmental benefits were enhanced by optimized DG in distribution network (Reddy *et al*., 2017, Sultana *et al*., 2017, Chen and Cheng, 2012). This study is crucial, having observed that both DG and EV will be very vital in future energy market. All these studies, however, ignored the future evaluation of EV load in its planning issue.

In the literature, limited studies (Jamian *et al*., 2014b) (Jamian *et al*., 2014a) and (Jamian, 2013) have adopted multiple approaches, such as analytical method (AM) (Jamian *et al*., 2014a, Jamian *et al*., 2014b) artificial bee colony (ABC) (Jamian *et al*., 2014b), and rank evolutionary particle swarm optimisation (REPSO) (Jamian, 2013) to solve the DG and BSS planning issues. AM lacks robustness (Tan *et al*., 2013), and hybrid techniques are difficult to implement (Tan *et al*., 2013), while ABC converges slowly due to stochastic nature (Sahoo, 2014). On the other hand, these proposed studies considered only the active power loss minimisation of the distribution system, while DG was operating at fixed location with unity power factor, and ignored current constraints. Therefore, the solution of the reported issues is needed to meet the target of the load demand with power quality;, it is imperative to introduce an innovative solution for optimum allocation of DG and battery charging stations for EVs. In addition, energy planners are required to implement more intellectual approach for optimal allocation of DG and BSS units in the distribution system, which is good in both exploration and exploitation, simple, and efficient. Therefore, authors have found that WOA has all the aforementioned features.

The main contribution of this study is to propose a new application of WOA for maximising the active and reactive energy loss reduction, which is considered as a multi-objective energy index, based on optimal allocation of multiple BSS and DG unit. Branch current can be increased in several lines of system due to integration of DG and BSS, so it is also considered with other system constraints. In this study, DG units are supplying both active and reactive power to the grid to enhance system benefits. In addition, the predetermined address of DG may lead to suboptimal solution (Kollu *et al*., 2013), hence , authors simultaneously determine the optimal site and size of DG. The presented approaches are tested on 33- and 69-bus radial distribution systems. Distribution system performance is analysed based on multiple technical criteria such as, system loading factor, voltage profile improvement, and active and reactive power loss reduction indices. Moreover, the performance of WOA is validated with and compared to the ABC and gravitational search algorithm (GSA). The simulation results reveal that the WOA-based optimisation technique is more efficient than comparative algorithms in terms of active and reactive energy loss reduction, and performance indices as well as its convergence properties.

PROBLEM FORMULATION AND OPERATIONAL CONSTRAINTS

To realise the optimal evolution and operation of a distribution system in the presence of a growing electrical load, energy planners consider multiple objectives simultaneously. The minimisation in active and reactive energy losses of distribution network was chosen as the multi-objective in this study. These objectives have been achieved via simultaneous placement of multiple DG and BSS units in the distribution system. Furthermore, the imposed equality and inequality constraints have been considered to ensure secure and reliable operation of the distribution system, DG and BSS units.

Active reactive energy index

In energy planning, the role of indices is very important. Usually, selection of the indices has a substantial effect on system's technical, economic, and environmental benefits. In the proposed study, active energy index (AEI) and reactive energy index (REI) are utilised for reducing active energy loss and reactive energy loss of the distribution system, respectively. The active reactive energy index (AREI) was mathematically modelled as a weighted sum of AEI and REI, and is expressed by equation (1).

$$AREI = w_{AE}AEI + w_{RE}REI \tag{1}$$

where w_{AE}= active energy weight factor and w_{RE}= reactive energy weight factor

$W_{AE}+W_{RE}=1$.

These AEI and REI can be expressed by equation (2) and equation (3), respectively. The values of active energy loss and reactive energy losses with and without DG and BSS units are expressed by equations (4)–(7). Furthermore, the active and reactive load values of wee days in summer season based on IEEE-RTS system (Wong *et al*., 1999) have been considered in this study. The active power loss and reactive power loss of each system were determined at every hour of a day with and without DG and BSS units based on equations (8)–(11). In this study, authors assumed that the same load profile of one day is repeated over the 365 days of one year.

$$AEI = \frac{\left|AE^{loss}_{system}\right|_{DG-BSS}}{\left|AE^{loss}_{system}\right|_{w/oDG-BSS}} \tag{2}$$

$$REI = \frac{\left|RE^{loss}_{system}\right|_{DG-BSS}}{\left|RE^{loss}_{system}\right|_{w/oDG-BSS}} \tag{3}$$

$$\left|AE^{loss}_{system}\right|_{w/oDG-BSS} = 365 * \sum_{hr=1}^{24} P^{loss}_{system}\Big|_{w/oDG-BSS} * T_{hr} \tag{4}$$

$$\left|AE^{loss}_{system}\right|_{DG-BSS} = 365 * \sum_{hr=1}^{24} P^{loss}_{system}\Big|_{DG-BSS} * T_{hr} \tag{5}$$

$$\left|RE^{loss}_{system}\right|_{DG-BSS} = 365 * \sum_{hr=1}^{24} Q^{loss}_{system}\Big|_{w/oDG-BSS} * T_{hr} \tag{6}$$

$$\left|RE^{loss}_{system}\right|_{w/oDG-BSS} = 365 * \sum_{hr=1}^{24} Q^{loss}_{system}\Big|_{w/oDG-BSS} * T_{hr} \tag{7}$$

where T_{hr} = time duration (1 hour), N_{br} = number of branches, while R_{bi}, and X_{bi} = resistance and reactance of the i^{th} branch, respectively.

$$P^{loss}_{system}\Big|_{DG-BSS} = \sum_{i=1}^{Nbr} \left|I^{DG-BSS}_{bi}\right|^{2} R_{bi} \tag{8}$$

$$Q^{loss}_{system}\Big|_{DG-BSS} = \sum_{i=1}^{Nbr} \left|I^{DG-BSS}_{bi}\right|^{2} X_{bi} \tag{9}$$

$$P^{loss}_{system}\Big|_{w/oDG-BSS} = \sum_{i=1}^{Nbr} \left|I^{w/oDG-BSS}_{bi}\right|^{2} R_{bi} \tag{10}$$

$$Q^{loss}_{system}\Big|_{w/oDG-BSS} = \sum_{i=1}^{Nbr} \left|I^{w/oDG-BSS}_{bi}\right|^{2} X_{bi} \tag{11}$$

The energy planner/operator can set the priority of the objective function based on weighting factors; in other words, a more important objective in the multi-objective function has a greater percentage value than others. In the proposed study, each objective has a 50% coefficient value.

Operational constraints of power system, DG units, and BSS units

The integration of DG and BSS units may change distribution line current. Therefore, the optimal flow of current in distribution lines has been considered with other power system, DG units, and BSS units operational constraints in order to ensure a safe and reliable operation of the distribution system after DG and BSS units placement.

- Active and reactive power conservation limits are considered as equality constraints:

$$\sum_{j=i}^{Nbus} P_j^{load} + \sum_{i=1}^{Nbr} P_{bi}^{loss} = \sum_{K=1}^{4} P_{DG}^{k} + P_{substation} \tag{12}$$

$$\sum_{j=1}^{Nbus} Q_j^{load} + \sum_{i=1}^{Nbr} Q_{bi}^{loss} = \sum_{K=1}^{4} Q_{DG}^{k} + Q_{substation} \tag{13}$$

- Node voltage limits should be kept within a prescribed range from 95% to 105% of the nominal voltage value:

$$1.05 \geq V_{\mathrm{j},new}^{bus} \geq 0.95 \qquad \text{where j=1,2, ….. } N_{bus} \tag{14}$$

- Line current limit is considered for avoiding the current increment in some branches after DG and BSS units inclusion:

$$I_{bi}^{DG-BSS} < I_{bi}^{\max} \qquad \text{where } i = 1,2,\ldots\ldots, N_{br} \tag{15}$$

- Active and reactive power operating limits of DG units should not be violated:

$$P_K^{DG,\min} \leq P_K^{DG,new} \leq P_K^{DG,\max} \qquad \text{where k= 1,2,3, and 4} \tag{16}$$

$$Q_K^{DG,new} = P_K^{DG,new} \tan\left(\cos^{-1}\left(p.f_{DG}\right)\right) \tag{17}$$

- The prescribed maximum limit of total active power of multiple DG units in the system must be greater than or equal to total real power of kth DG units supply in the system:

$$P_{total}^{DG,\max} \geq \sum_{K=1}^{4} P_K^{DG,new} \tag{18}$$

- A power consumption limit of each BSS unit is equal to the demand of ten charging slots:.

$$P_{unit}^{BSS} = 10 * P_{ChS}^{BSS} \tag{19}$$

- Allowable number of BSS units is limited to fewer than 3:
- Number of BSS units on single bus 2 (20)

Evaluation of indices for multiple DG and BSS units placement

The effect of multiple DG and BSS units' simultaneous placement on the performance of distribution systems is appraised based on evaluation indices. The mathematical formulations of these indices are presented in Table 1 (Aman *et al*., 2013, Ettehadi *et al*., 2013). The higher percentage values of all these indices represent the better performance of the distribution system. Moreover, a value of *LFEI* (%) closer to zero warns the system operator that the system is near to voltage collap

Table 1. Evaluation indices of multiple DG and BSS units placement.

Analysis parameters	Formulae
Active Power Loss Reduction Index (APLRI)	$APLRI = \left(\frac{P^{loss}_{system}\big\vert_{w/oDG-BSS} - P^{loss}_{system}\big\vert_{DG-BSS}}{P^{loss}_{system}\big\vert_{w/oDG-BSS}} \right) *100$ (%)
Reactive Power Loss Reduction Index(RPLRI)	$RPLRI = \left(\frac{Q^{loss}_{system}\big\vert_{w/oDG-BSS} - Q^{loss}_{system}\big\vert_{DG-BSS}}{Q^{loss}_{system}\big\vert_{w/oDG-BSS}} \right) *100$ (%)
Voltage Profile Improvement Index (VPII)	VPII= $\left(\frac{\sum_{j=1}^{Nbus} \left(\left\vert V_j^{bus} \right\vert_{DG-BSS} * \left\vert load_j^{bus} \right\vert_{DG-BSS} \right) - \sum_{j=1}^{Nbus} \left(\left\vert V_j^{bus} \right\vert_{w/oDG-BSS} * \left\vert load_j^{bus} \right\vert_{w/oDG-BSS} \right)}{\sum_{j=1}^{Nbus} \left(\left(\left\vert V_j^{bus} \right\vert_{w/oDG-BSS} * \left\vert load_j^{bus} \right\vert_{w/oDG-BSS} \right) \right)} \right) *100$ (%)
Load Factor Enhancement Index (LFEI)	$LFEI = \left(\frac{\left\vert LF^{\max}_{system} \right\vert_{DG-BSS} - \left\vert LF^{\max}_{system} \right\vert_{w/oDG-BSS}}{\left\vert LF^{\max}_{system} \right\vert_{w/oDG-BSS}} \right) *100$ (%)

WHALE OPTIMISER ALGORITHM AND OPTIMAL ALLOCATION OF DG AND BSS UNITS

Mirjalili and Lewis mimicked the hunting attitude of humpback whales and proposed a new meta-heuristic optimization algorithm, namely, whale optimiser algorithm (WOA) (Mirjalili and Lewis, 2016). The whales exhibit a special behaviour called bubble-net feeding, in which, the whales create bubbles via a '9' shaped path or encircling while searching for food (Prakash and Lakshminarayana, 2016). The mathematical model of searching prey, encircling prey, and spiral bubble-net feeding behaviour is first presented, and the WOA algorithm is then proposed (Mirjalili and Lewis, 2016).

Prey searching and encircling

Most importantly, location of prey can easily be recognized by humpback whales, and they encircle their victim. In (Mirjalili and Lewis, 2016), the behaviour of searching and encircling is modelled based on equations (21) and (22) , respectively:

$$\left.\begin{aligned} \vec{D} &= \left|\vec{Q} \bullet \vec{X}_{rnd} - \vec{X}\right| \\ \vec{X}\left(It+1\right) &= \vec{X}_{rnd} - \vec{B} \bullet \vec{D} \end{aligned}\right\} \quad (21)$$

$$\left.\begin{aligned} \vec{D} &= \left|\vec{Q} \bullet \vec{X}_p\left(It\right) - \vec{X}\left(It\right)\right| \\ \vec{X}\left(It+1\right) &= \vec{X}_p\left(It\right) - \vec{B} \bullet \vec{D} \end{aligned}\right\} \quad (22)$$

where $\vec{X}$ and $\vec{X}_p$ = position vector and best position vector so far, respectively.

$\vec{X}_{rnd}$= random position vector, It= Current iteration. The coefficient vectors $\vec{B}$ and $\vec{Q}$ are calculated using equations (23) and (24), respectively. However, the values of lie randomly in the gap [-b, b] and Q contains values in the interval [0, 2].

$$\vec{B} = 2\vec{b} \bullet \vec{rnd}_1 - \vec{b} \quad (23)$$

$$\vec{Q} = 2 \bullet \vec{rnd}_2 \quad (24)$$

Moreover, the random vectors are denoted by rnd1 and rnd2 over a range of [0,1]. The component $\vec{b}$ linearly decreases from 2 to 0 over the span of iterations.

Bubble net attacking approach

Two approaches, namely, shrinking encircling mechanism and spiral updating position, are utilized to model mathematically, the bubble-net attitude of humpback (Mirjalili and Lewis, 2016). The value of b in equation (23) is decreased to depict the shrinking behavior. The possible positions of the search agents from (X, Y) towards (X_P, Y_P), which can be achieved by $0 \le B \le 1$ in a 2D space, is are shown in Figure 1 (Mirjalili and Lewis, 2016).

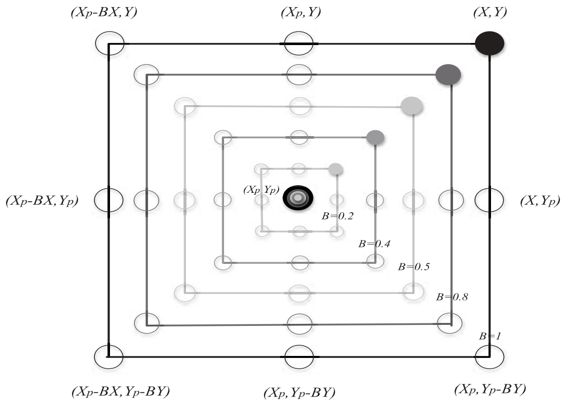


Figure.1. Shrinking encircling mechanism.

Shrinking circle and spiral-shaped path are taken by the humpback whales simultaneously to hunt their preys (Mirjalili and Lewis, 2016). In modeling, this behaviour, a 5050- scenario is assumed for each of the paths to update the whales' position (Mirjalili and Lewis, 2016).

$$\vec{X}\left(It+1\right)=\vec{X}_{p}\left(It\right)-\vec{B}\bullet\vec{D} \tag{25}$$

$$\vec{X}\left(It+1\right)=\vec{D}^{/}\bullet e^{dk}\bullet\cos\left(2\pi k\right)+\vec{X}_{p}\left(It\right) \tag{26}$$

where $\vec{D}^{/}$, d, k, P and • are the distance of the jth whale to the prey, a constant describing the shape of the logarithmic spiral, a random number in [−1,1], a random number in [0,1], and an element-by-element multiplication, respectively.

The WOA-based methodology is applied to determine the optimal location and size of multiple DG units and optimal bus addresses of BSS units with its predefined ratings. Figure 2 shows the flow chart for simultaneous placement of multiple DG and BSS units. The following steps are taken to solve optimisation problems of simultaneous placement.:

Step 1: The initial data of system, number of search agents (Nsa), problem dimension (dim), It, max-It, and maximum and minimum limits of DG operating size and location of DG and BSS units are read.

Step 2: The variables, such as output power of DG, bus numbers of DG, and BSS placement, are generated randomly;, then normalize all these between upper and lower operating boundaries. Moreover, the random numbers are denoted by Rand over the range of [0,1]. Equation (27) is utilised for this purpose:

$$variable_{new}^{K}=Rand*(\mathrm{varable}_{\max}^{K}-\mathrm{variable}_{\min}^{K})+\mathrm{variable}_{\min}^{K} \tag{27}$$

where K= 1,2,….,*dim*

where the new value, minimum value, and the maximum value of randomized generated variables are denoted by, $Variable_{new}^{K}$, $Variable_{\min}^{K}$, and $Variable_{\max}^{K}$, respectively.

The initial population of search agents, such as DG capacity (P_{DG}^{N}), bus location of DG (Loc_{DG}^{LD}), and bus address of BSS (Loc_{BSS}^{LB}), is represented by a vector X^{K} for the optimal simultaneous placement issue

$$\begin{aligned}X^{K}&=P_{DG}^{1,K},P_{DG}^{2,K},......\mathrm{P}_{DG}^{\mathrm{N},K},Loc_{DG}^{1,K},Loc_{DG}^{2,K},......\\&...........Loc_{DG}^{\mathrm{LD},K},Loc_{BSS}^{1,K},Loc_{BSS}^{2,K},........Loc_{BSS}^{\mathrm{LB},K}\end{aligned} \tag{28}$$

where, N= number of DG; LD=possible locations for DG placement; LB = possible locations for BSS placement. Equation (29) represents the initial complete solution of vector X that is generated for the total number of search agents.

$$X=X^{1},X^{2},X^{3}.........X^{K}......X^{N_{sa}} \tag{29}$$

Step 3: The value of It is checked; if it has not reached the maximum limit (max-It), then Thukaram load flow theorem (Thukaram *et al.*, 1999) needs to be run to obtain specified constraints and *AREI*. Otherwise, Step 5 is next. The main characteristics of the load flow theorem are low memory consumption, robust convergence, and computational (Sultana *et al.*, 2016b).

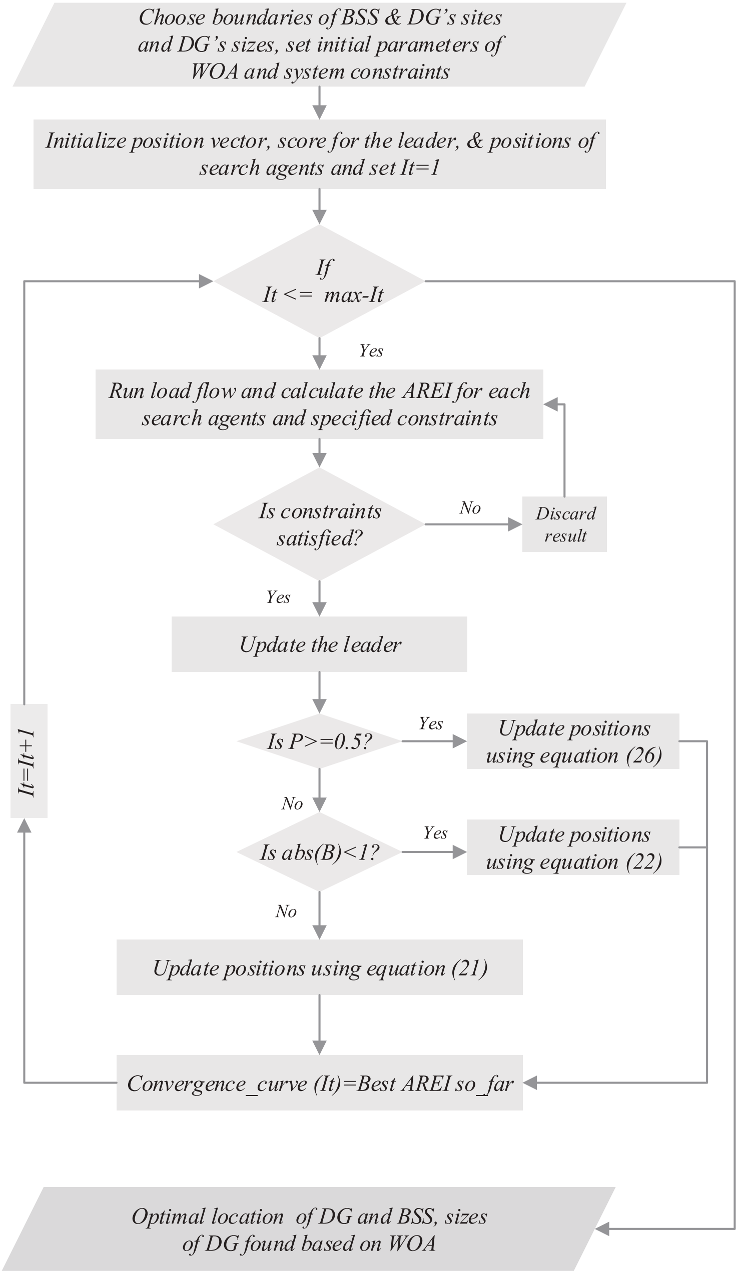


Figure .2. Flow chart of WOA.

effectiveness (Tan *et al*., 2012). *AREI* is considered in case of constraints are satisfied; otherwise, the results are discarded.

Step 4: The value of the leader is updated. Next, the positions of search agents are upgraded according to the values of *P* and *B* based on equations (21), (22), and (26). Now, the best objective function value is saved for the current iteration.

Step 5: The optimum locations of DG and BSS units, as well as DG size, are also finalized after stopping the simulations. Moreover, the optimal results satisfied the operational constraints of the system, DG units and BSS units. Finally, the convergence curve of the proposed methodology is drawn.

SIMULATION RESULTS

Test systems

The proposed research methodology was tested on 33-bus and 69-bus radial distribution systems.

33-bus radial distribution system

Figure 3(a) shows the one line diagram of the system, which has 32 branches and 33 buses, namely, the 33-bus distribution system. The total power fed from the infinite bus in the default case is 4.369 MVA (Aman *et al*., 2014). The base apparent power of the system was taken as 100 MVA.

69-bus radial distribution system

The 69-bus radial distribution system's single line diagram is given in Figure 3(b) (Aman *et al*., 2014). This operates at 12.66 kV and 100 MVA base values. The total load demand in terms of active and reactive power is 3.8 MW and 2.69 MVAr, respectively.

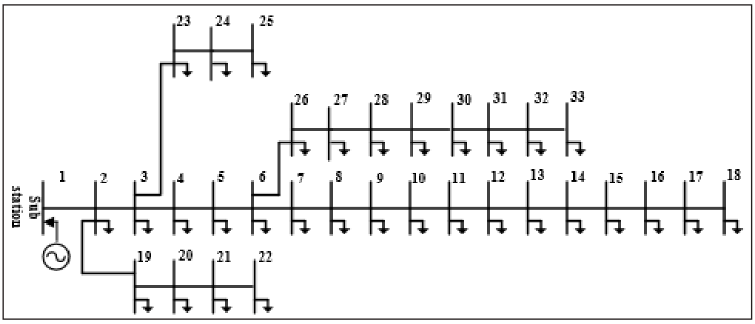


Figure. 3(a). Single line diagram of 33-bus distribution system.

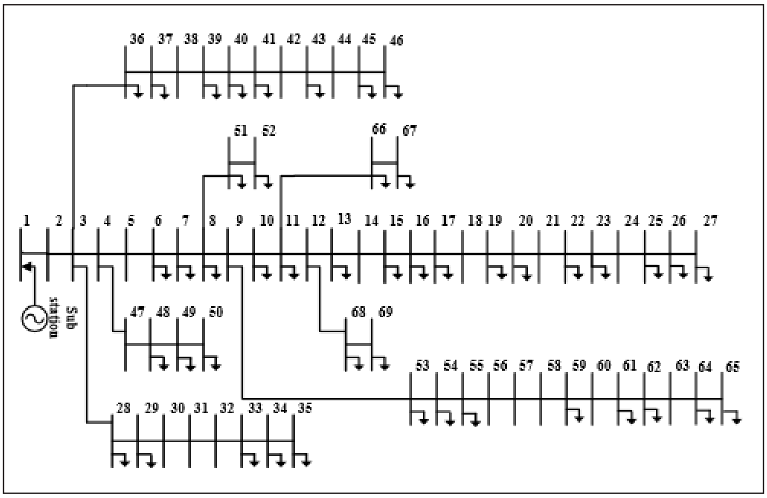


Figure. 3(b). Single line diagram of 69-bus distribution system.

Comparative study of WOA with ABC and GSA for simultaneous placement

In this section, authors validate and compare the performance of WOA with well-known methods, such as GSA and ABC on 33- and 69-bus systems. Originally, Rashedi et al. introduced GSA, and Karaboga proposed ABC in (Rashedi et al., 2009) and (Karaboga, 2005), respectively. These techniques have good computational characteristics. In the proposed study, authors assumed 100 iterations as a stopping criterion of simulation of all the three methods. In this study, four DG and four BSS units were considered in problem simulations, and the same types of model of all DG units considered were synchronous-based generators operating at 0.9 leading power factor (Sultana *et al*., 2016b). According to IEEE P1547 standard (2003), the presence of DG in the grid should not influence the voltage regulation of the distribution system. Any DG unit should follow the voltage regulation scheme set by the utility (Al Abri *et al*., 2013). Therefore, in all the analysis in this research, DG is considered operating with PQ controller, or the DG bus is modelled as a PQ bus. Also, level 2 charging station (BSS) is selected, which has 10 charging slots; each slot consumed 7.7 kW power (Jamian *et al*., 2014b). The real power consumption of level 2 charging slot (BSS unit) is higher than imaginary power;, therefore, the reactive power components of charging equipment are ignored (Jamian, 2013).

The generated optimal locations of DG and BSS units as well as the output power of DG for all distribution systems, after applying all the proposed and comparative algorithms, are given in Tables 2(a) and 2(b). Table 3(a) depicts the comparative results of the applied algorithms on 33-bus, and Table 3(b) shows comparative outcomes for the 69-bus distribution system for simultaneous placement of both BSS and DG units. On the other hand, based on WOA, Figures 4(a) and 4(b) are obtained, which represent the active and reactive energy of 33-bus and 69-bus systems with and without considering DG and BSS units, respectively,. *AEI* and *REI* of the proposed and existing algorithms are shown in Figures 5(a) and 5(b) for 33-bus and 69-bus networks, respectively. The *APLRI* and *RPLRI* based on WOA, GSA, and ABC for 33-bus and 69-bus systems are represented in Figure 6(a). Figure 6(b) shows the *VPII* and *LFEI* in terms of percentage based on applied methods for both test systems. The comparison among applied methodologies for active and reactive energy loss reduction is highlighted in Figures 7(a) and 7(b) for 33-bus and 69-bus distribution systems, respectively. The voltage profile curve of 33-bus and 69-bus systems for various simulations is represented in Figures 8(a) and 8(b), respectively. The convergence graphs for 33-bus and 69-bus system are shown in Figures 9(a) and 9(b), respectively. In addition, the computational analysis based on WOA, GSA, and ABC is presented in Table 4.

Table 2(a). Optimal bus numbers of BSS and DG units and output power of DG for 33 bus distribution system.

Methods	WOA	ABC	GSA
DG location (bus number)	7,13,25, & 30	13,19,24, & 29	3,11,25, & 28
DG size (MVA)	0.9,0.5,0.6, &1	0.9,0.9,1, & 1	0.6,1.1,0.9, &0.9
BSS location (bus number)	3,4,20, & 27	16,16,19, & 23	18,23,25, & 25

Table 2(b). Optimal bus numbers of BSS and DG units and output power of DG for 69-bus distribution system.

Methods	WOA	ABC	GSA
DG location (bus number)	9,17,38,& 61	36,50,59,& 62	26,38,49,& 62
DG size (MVA)	0.8,0.6,0.6,& 1.5	0.7,0.8,1.1,& 0.9	0.7,0.7,0.7,& 1.3
BSS location (bus number)	21,31,51, & 53	36,40,47,& 47	27,37,44,& 50

Table 3(a). Comparative results of applied algorithms on 33-bus distribution system for simultaneous placement.

Analyses	P^{loss}_{system} (MW)	Q^{loss}_{system} (MVA)	AE^{loss}_{system} (MWh)	RE^{loss}_{system} (MVArh)	$V^{bus}_{\max}$ (pu)	$V^{bus}_{\min}$ (pu)	$LF^{\max}_{system}$ (pu)	$AREI$ (pu)
Base case	0.211	0.143	3.5574	2.4105	1.00	0.9038	3.41	1.00
WOA	**0.0212**	**0.0156**	**0.3814**	**0.3006**	**1**	**0.9751**	**4.09**	**0.1159**
ABC	0.029	0.0213	0.4852	0.3568	1	0.9724	3.88	0.1422
GSA	0.0338	0.0254	0.6389	0.4805	1	0.968	3.86	0.1895

Table 3(b). Comparative results of applied algorithms on 69-bus distribution system for simultaneous placement.

Analyses	P^{loss}_{system} (MW)	Q^{loss}_{system} (MVAr)	AE^{loss}_{system} (MWh)	RE^{loss}_{system} (MVArh)	$V^{bus}_{\max}$ (pu)	$V^{bus}_{\min}$ (pu)	$LF^{\max}_{system}$ (pu)	$AREI$ (pu)
Base case	0.225	0.1021	3.7862	1.7205	1.000	0.9092	3.21	1.00
WOA	**0.0191**	**0.0131**	**0.3175**	**0.2227**	**1.0007**	**0.9789**	**3.98**	**0.1066**
ABC	0.0332	0.0146	0.6119	0.2616	1	0.9709	3.93	0.1569
GSA	0.0379	0.0176	0.5834	0.2643	1.003	0.9684	3.83	0.1539

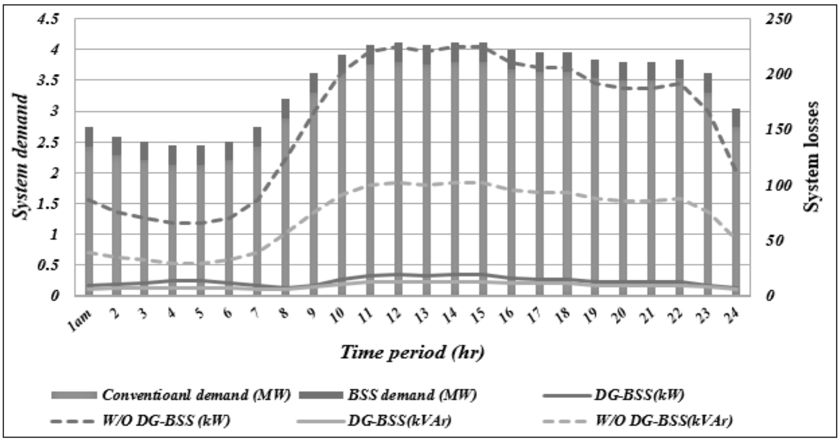


Figure. 4(a). Active and reactive energy losses before and after DG-BSS allocation in 33-bus distribution system based on WOA.

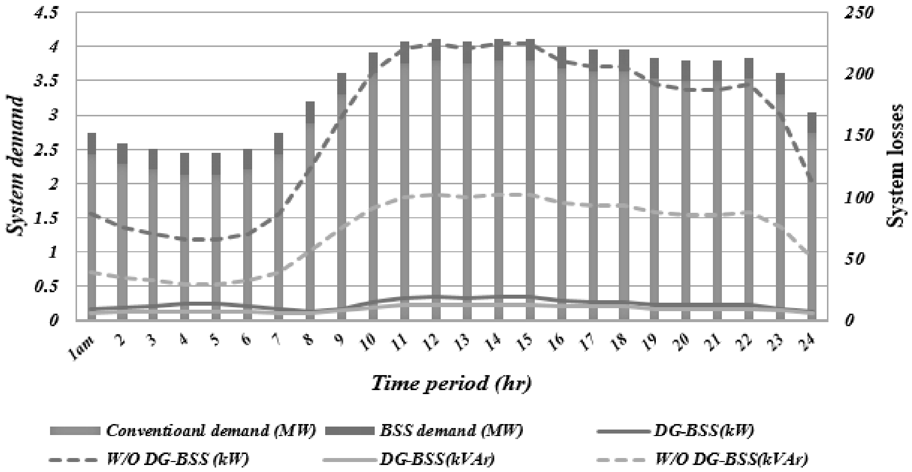


Figure. 4(b). Active and reactive energy losses before and after DG-BSS allocation in 69-bus distribution system based on WOA.

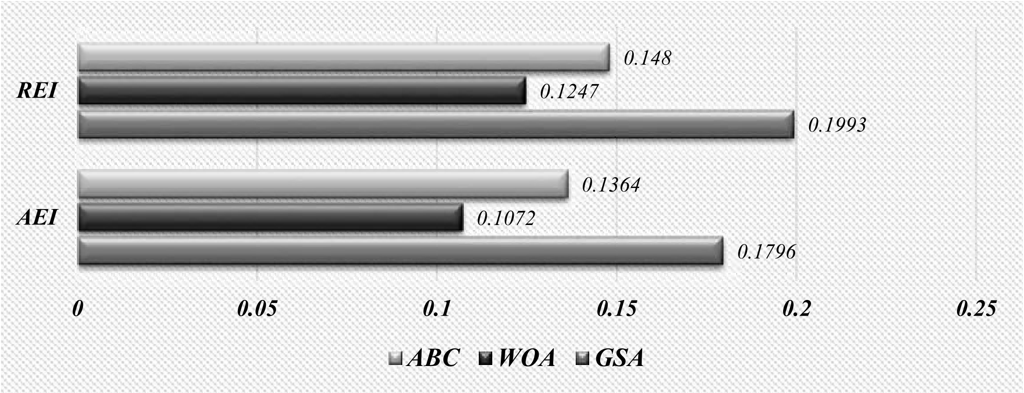


Figure. 5(a). AEI and REI of the proposed and existing algorithms in 33-bus distribution system.

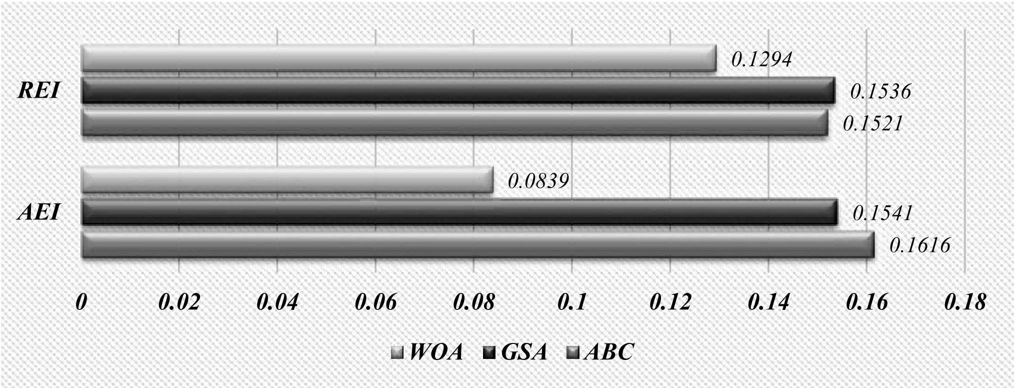
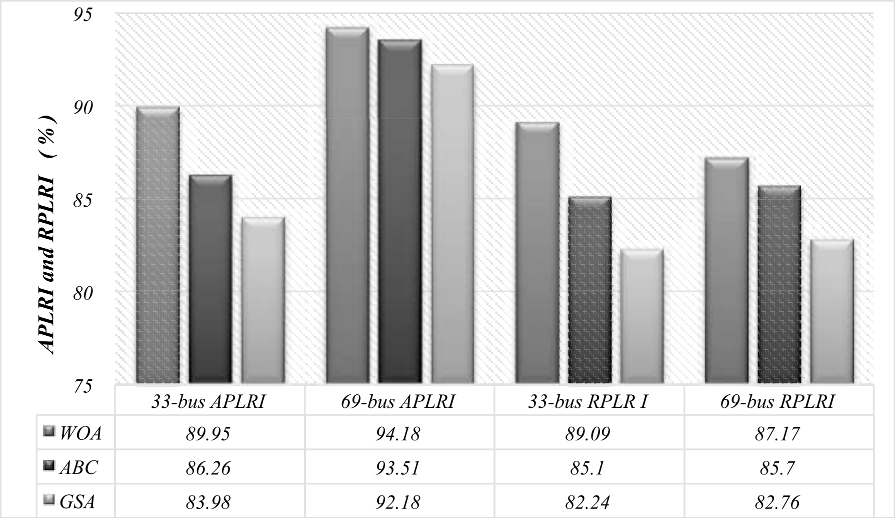
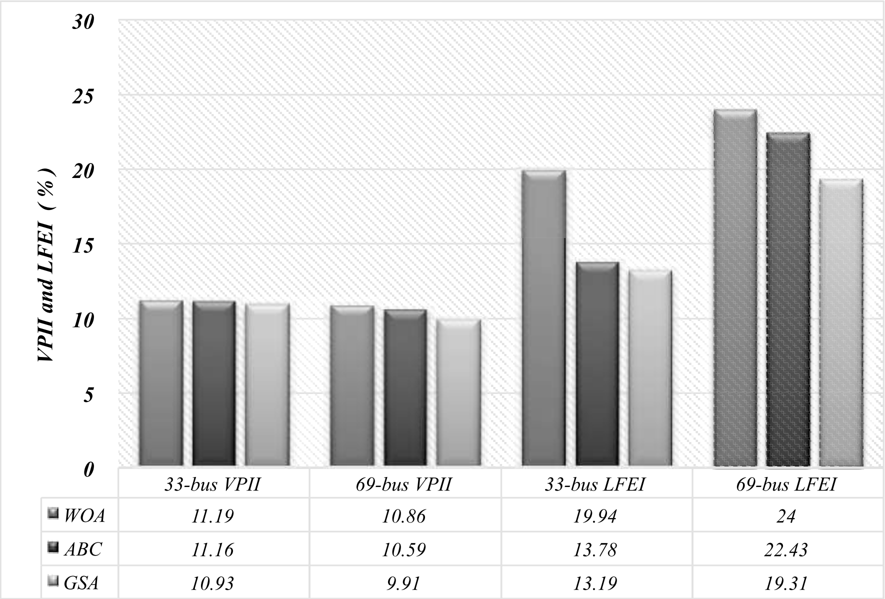


Figure. 5(b).AEI and REI of the proposed and existing algorithms for 69-bus distribution system.



	33-bus APLRI	69-bus APLRI	33-bus RPLR I	69-bus RPLRI
■ WOA	89.95	94.18	89.09	87.17
■ ABC	86.26	93.51	85.1	85.7
■ GSA	83.98	92.18	82.24	82.76

Figure. 6(a). Comparison of loss reduction of all presented algorithms for the two bus systems.



	33-bus VPII	69-bus VPII	33-bus LFEI	69-bus LFEI
■ WOA	11.19	10.86	19.94	24
■ ABC	11.16	10.59	13.78	22.43
■ GSA	10.93	9.91	13.19	19.31

Figure. 6(b). Comparison of systems loading and voltage profile of all presented algorithms for the two bus systems.

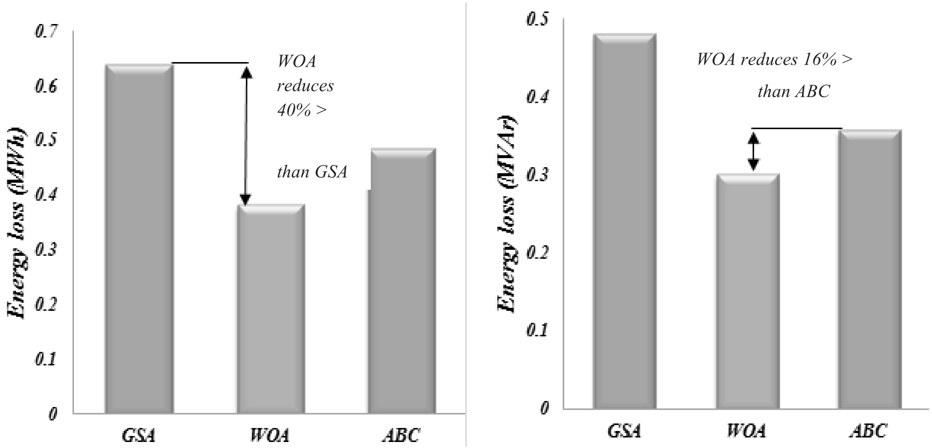


Figure. 7(a). Comparison among applied methodologies for active and reactive energy loss reduction in 33-bus distribution system.

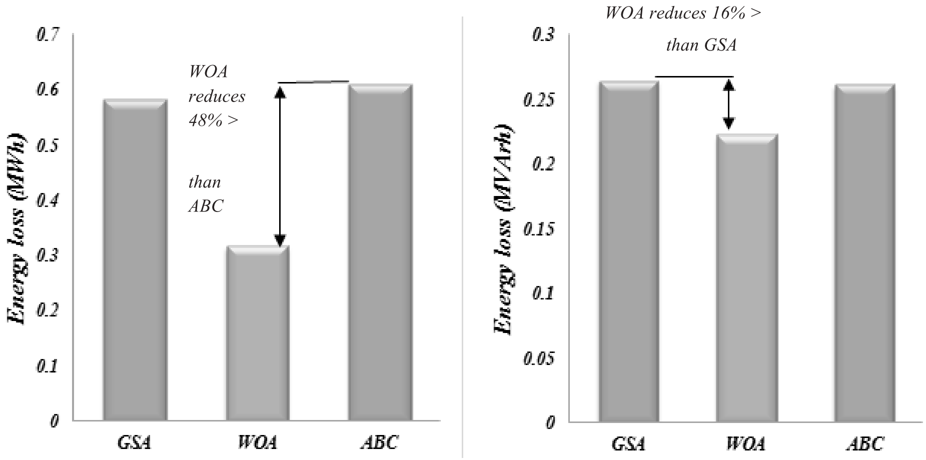


Figure. 7(b). Comparison among applied methodologies for active and reactive energy loss reduction in 69-bus distribution system.

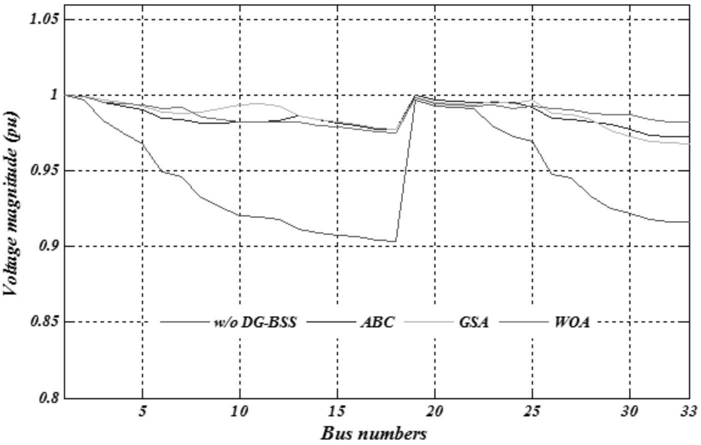


Figure. 8(a). Voltage profile of 33-bus distribution system simultaneously.

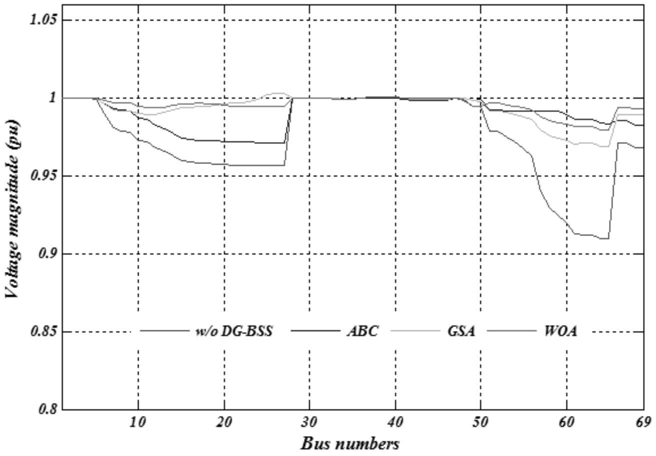


Figure. 8(a). Voltage profile of 69-bus distribution system simultaneously.

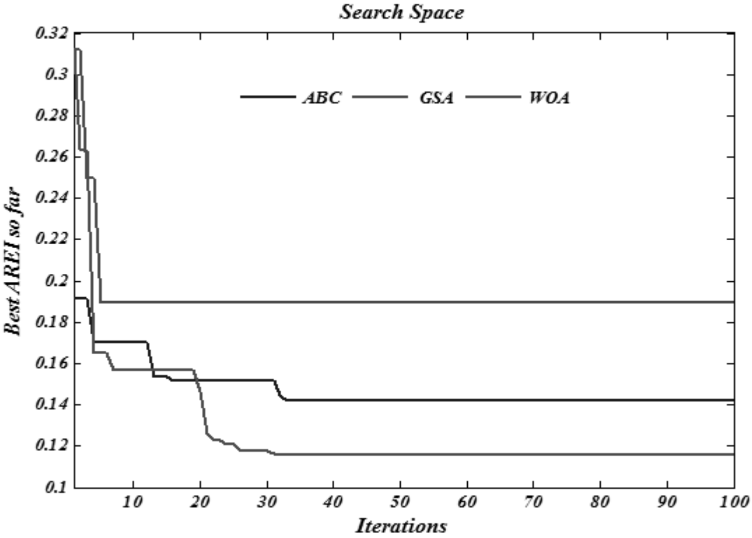


Figure. 9(a). Convergence characteristic curves of proposed method and comparative algorithms for 33-bus system

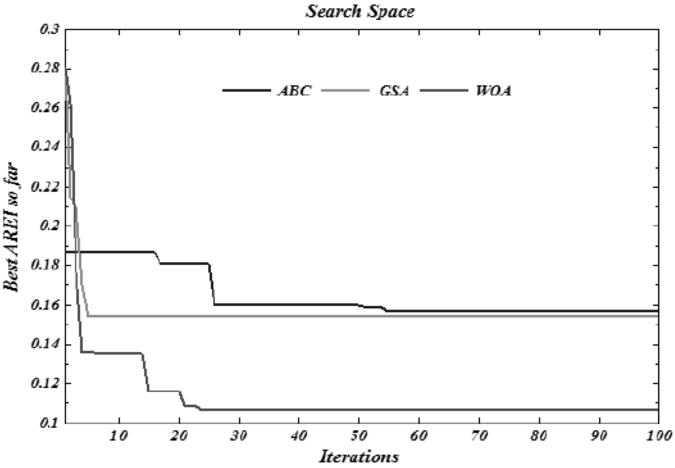


Figure. 9(b). Convergence characteristic curves of the proposed method and comparative algorithms for 69-bus system.

Table 4. Computational statistics of optimisation methods for simultaneous allocation of DG and BSS units.

Methods	Best *AREI*	Worst *AREI*	Average	Standard deviation	Relative Standard deviation	Average elapsed time (sec)
33-bus system						
WOA	0.11596	0.11610	0.11599	$1.25\text{x}10^{-6}$	0.0000107	118.89627
ABC	0.14220	0.15242	0.14831	$2.47\text{x}10^{-5}$	0.000166	255.55781
GSA	0.18947	0.19910	0.19423	$1.99\text{x}10^{-5}$	0.000102	160.93545
69-bus system						
WOA	0.10665	0.10669	0.10667	$3.49\text{x}10^{-6}$	0.0000327	224.68834
ABC	0.15691	0.16101	0.15812	$7.68\text{x}10^{-5}$	0.0004857	659.93476
GSA	0.15386	0.15908	0.15622	$6.39\text{x}10^{-5}$	0.0004090	392.18632

DISCUSSION

The following points are noted after validation and comparison of WOA with gravitational search, and artificial bee colony algorithms are analysed.

- In Table 2(a), after applying all the three methods, there is no common bus location obtained based on all applied methods for BSS placement. However, the same bus address, such as 13, has been found for DG allocation after applying WOA and ABC. In Table 2(b), it is clearly observed that bus number 36 is a common location of DG and BSS units based on ABC. However, the DG rating 0.8 MVA is common in WOA and ABC techniques. In Tables 3(a) and 3(b), the bold values show the best value among the all applied algorithms. It is noticed from Table 3(a) that, all the performance parameter values of the 33-bus distribution network have been improved based on ABC in comparison with GSA. However, in Table 3(b), more active and reactive power losses and reactive energy loss have been reduced based on ABC as compared to GSA. On the other hand, in 33- and 69-bus systems, the WOA based methodology provides significantly improved outcomes than both comparative algorithms, namely, ABC and GSA.

- From Figures 8(a) and 8(b), the voltage magnitudes of all buses are significantly improved based on all applied algorithms, and the system operates under the prescribed limit of voltage ($0.95 <= V_{j,new}^{bus} <= 1.05$). However, voltage profile from buses 28 to 48 is almost equivalent based on all algorithms.

- The active and reactive power losses follow the load pattern in the absence of DG-BSS as observed in Figures 4(a) and 4(b). This means that incremental power losses may be incurred on further addition of load. However, from 12 midnight to 8 am, when the total load (i.e., conventional and BSS) is less than 70% of peak load and DG and BSS are allocated, the losses profiles are reciprocal to the load profile due to distributed generator characteristics. It can be observed that, based on the proposed method (WOA), the losses are drastically reduced from its base value (i.e., without DG-BSS) for every hour during the presence of peak and BSS load. Hence, the energy losses also reduced for both 33- and 69-bus systems.

- The order of both indices such as *AEI* and *REI* values from highest to lowest based on GSA, ABC, and WOA is noticed in Figure 5(a). But in Figure 5(b), value of *AEI* based on ABC is slightly higher than GSA. The smallest value of the indices based on the WOA approach indicates better performance for the distribution system than other approaches.

- The statistical results from Figure 6(a) show that the lowest values of *APLRI* and *RPLRI* have been found based on GSA for 33-bus and 69-bus systems. In both systems, the *RPLRI* has highest value based on WOA. It is indicated that more reactive power has been conserved in the electricity grid; this saving may help enhance the loadability of the system, as well as reducing system up-gradation. On the other hand, it is observed from Figure 6(b), that about the same value of *VPII* has been obtained based on WOA and ABC for both distribution systems, but *LFEI* based on WOA is higher than ABC and GSA based approaches.

- In Figure 7(a), the statistical values showed that the WOA based methodology reduced 40% AE_{system}^{loss} and 16% RE_{system}^{loss} more than GSA and ABC, respectively, in AE_{system}^{loss} the 33-bus system. On the other hand, in Figure 7(b), the reduction in based on WOA is 48% more as compared with to ABC based technique. In the comparison between ABC and GSA, the AE_{system}^{loss} reduction based on ABC is higher than GSA in the 33- bus system, but it is vice versa in the 69-bus system. Finally, all results obtained via WOA were far better than ABC and GSA.

- In Figures 9(a) and 9(b), it can be observed that all the three methodologies converge smoothly to show the reliability of optimisation methods. However, neither very slow convergence, such as ABC, nor premature convergence, like GSA, has been observed by WOA, which led to the generation of a high-quality solution. These figures show that the least values of *AREI* have been found based on WOA for both bus systems, which provide the best optimal sites and sizes of DG and BSS in order to reduce highest energy losses of the systems.

- The solutions generated using WOA, ABC, and GSA were then tabulated in Table 4 after 15 trials. In these results, lowest relative standard deviation was found in WOA techniques, which indicates the strong output consistency of the proposed method as compared to other algorithms. Moreover, the proposed method (WOA) takes lowest processing time compared to the other two approaches.

CONCLUSIONS

In this study, an application of WOA has been presented for optimal placement of multiple BSS units and DG for minimising active and reactive energy losses, and improving the voltage profile. The simultaneous placement based approach for multiple DG and BSS units, has been adopted. Branch currents can be increased in few lines in the presence of BSS and DG units; therefore, the current constraint was, in addition, considered with the other power system constraints. These approaches were examined on 33- and 69-bus distribution systems. The efficiency of the power system was evaluated based on different performance indices. Furthermore, in order to evaluate

WOA, well-known techniques, namely, ABC and GSA, have been utilized as benchmarks. It can be observed, on the basis of simulation results, that the WOA based optimisation technique is more effective than other algorithms in terms of active and reactive energy loss minimisation, as well as maintaining both phases, namely, exploration and exploitation of the optimal solution, to obtain a quality solution. The proposed algorithm has the capability of handling complex optimisation issues of optimal DG and BSS units planning.

- Energy planners in distribution companies can utilize the proposed approach to achieve optimal energy loss reduction when planning DG and BSS units in their systems without compromising system limits. This will provide abetter assessment of integration proposals of DG and BSS units in the distribution system for its optimal and reliable operation.

- The developed methodology can be extended further to account for consideration of CO2 emission and cost of energy related to electricity generation based on renewable energy, such as wind, solar.

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محطات توليد موزعة ووحدات تبديل البطارية لتشغيل المركبات الكهربائية باستخدام خوارزمية whale optimiser

يو سلطانا *، أزهر خير الدين**، نادية رشيد***، ساجد حسين غازي**** وآيه إس مختار**

* قسم الهندسة الكهربائية، جامعة NED للهندسة والتكنولوجيا، كراتشي، باكستان

** قسم هندسة الطاقة الكهربائية، جامعة ماليزيا للتكنولوجيا، جهور، ماليزيا

*** جامعة كلية الهندسة والتكنولوجيا، الجامعة الإسلامية في باهاوالبور، باهاوالبور، باكستان

**** قسم الهندسة الكهربائية، حرم UET SZAB بمهران، خيرابور ميراس، باكستان

الخـلاصة

مع تزايد الطلب على المركبات الكهربائية (EVs) في نظام التوزيع الحالي بسبب استدامة حركة المرور على الطرق، وخفض تكاليف الوقود وتحسين البيئة من خلال تعزيز الكربونات المنخفضة في وسائل النقل، يحتاج مخططو الأنظمة إلى التقليل من الخسائر في الطاقة وتحسين الجهد الكهربائي في الشبكة. وفي دراسات قليلة تم حل تلك المسائل بواسطة تحديد المكان الأمثل لوحدات التوليد الموزعة (DG) ومحطات تبديل البطارية (BSS) في نظام التوزيع ؛ ومع ذلك، نظرت هذه التقنيات إلى الحد الأدنى من فقدان الطاقة النشطة فقط مع قيود منهجية مختلفة. لذلك، تم اقتراح تطبيق جديد لخوارزمية whale optimizer (WOA) لحل تلك القيود. وقد تم اعتماد النهج المتزامن القائم على وضع الوحدات لتقليل الفاقد في الطاقة النشطة والتفاعلية في أنظمة توزيع 33 و69 حافلة. تم تحليل أداء النظام بناءً على معايير تقنية متعددة، مثل عامل تحميل النظام، وتحسين أداء الجهد الكهربي، ومؤشرات خفض فاعلية الطاقة النشطة والتفاعلية. وقد أثبتت نتائج WOA أنها متفوقة على تلك الخاصة بخوارزميات مجتمع النحل الاصطناعي (bee colony) وبحث الجاذبية (gravitational search). ولذلك، يمكن للمنهجية المقترحة توجيه مخططي الطاقة في تحديد التوزيع الأمثل لوحدات DG وBSS المتعددة في أنظمتهم؛ بالإضافة إلى الحد من فقدان الطاقة المتوقع داخل النظام، BSS، وتخطيط DG والقيود التشغيلية.