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Optimal Planning of Renewable Energy-Integrated Distribution System Considering Uncertainties

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ABSTRACT Optimal planning of renewable energy-based DG units (RE-DGs) in active distribution systems (ADSs) has many positive technical and economical implications and aim to increase the overall system performance. The optimal allocation and sizing of RE-DGs, particularly photovoltaic (PV) and wind turbine (WT), is still a challenging task due to the stochastic behavior of renewable resources. This paper proposed a novel methodology to solve the problem of RES-DGs planning optimization based on improved Harris Hawks Optimizer (HHO) using Particle Swarm Optimization (PSO). The uncertainties associated with the intermittent behaviour of PV and WT output powers are considered using appropriate probability distribution functions. The optimization problem is formulated as a non-linear constrained optimization problem with multiple objectives, where power loss reduction, voltage improvement, system stability, and yearly economic saving have been taken as the optimization objectives taken into account various operational constraints. The proposed methodology, namely HHO-PSO, has validated on three test systems; standard IEEE 33 bus and 69 bus systems and 94 bus practical distribution system located in Portuguese. The obtained results reveal that the HHO-PSO provide better solutions and maximizes the techno-economic benefits of the distribution systems for all considered cases and scenarios. Furthermore, simulation results are evaluated by comparing to those well-known approaches reported in the recent literature.

INDEX TERMS Renewable energy, distributed generation, distribution system planning, uncertainties, Harris hawks optimizer, particle swarm optimization.

NOMENCLATURE

Acronyms

ABC	artificial bee colony
BB-BC	big bang–big crunch method
ADS	active distribution system
BFOA	bacterial foraging optimization algorithm
BSA	backtracking search algorithm
BSOA	backtracking search optimization algorithm
CDF	cumulative density functions.
CS-GA	cuckoo search-generic algorithm
DA	dragonfly algorithm
DG	distributed generator
FA	firefly algorithm
HGWO	grey wolf optimizer
IDSA	improved differential search algorithm
IWD	intelligent water drop algorithm
KH	krill herd algorithm
LSF	loss sensitivity factor
MCS	monte carlo simulation
MINLP	mixed integer non-linear programming
MOCD	multi-objective opposition based chaotic differential evolution algorithm
MOEA/D	multi-objective evolutionary algorithm based on decomposition
MTLBO	modified teaching–learning based optimization
PDF	probability distribution functions.
PSO	particle swarm optimization

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PSO-DE	particle swarm optimization with differential evolutionary
PV	Photovoltaic
QOTLBO	quasi-oppositional teaching learning-based optimization
RES	renewable energy source
SKHA	stud krill herd algorithm
WOA	whale optimization algorithm
WT	wind turbine
Indices and Sets	
b	index of system branches
i	index of system buses
m	index of DGs
NB	set of system buses
NBR	set of system branches
NDG	set of system DGs
$N_{iter}, _{max}$	set of iterations
N_{pop}	set o population size
N_{runs}	set of individual runs
Parameters and Constants	
μ	the total DG penetration level
C, k	scale and shape parameters of Weibull function
C_{DG}	the cost of injected power via DG per kW
C_E	the average cost of energy loss per kWh
$g_{ij,b}$	the conductance of branch b connecting the ith and jth buses
$PFDG, max$	the maximum allowable power factor of mth DG
$PFDG, min$	the minimum allowable power factor of mth DG
P_{PVr}	the rated output power of the photovoltaic unit
P_{WTr}	rated power of wind turbine
r	rate of intreset on capital investment of the installed DG
R_c	the certain irradiance point
$r_{ij,b}$	the resistance of the branch b connecting the ith and jth buses
S_b	the apparent power flow through bth branch
Sb, max	the maximum thermal capacity of bth branch
SDG, max	the allowable maximum size of mth DG
S_{STC}	the solar irradiance at standard test conditions
T_{DG}	the total DG lifetime in years
v_{ci}	cut-in wind speed of the wind turbine
v_{co}	cut-out wind speed of the wind turbine
Vi, ref	the magnitude of the reference voltage at bus i
V_{max}	the maximum allowable value of bus voltage
V_{min}	the minimum allowable value of bus voltage
v_r	rated wind speed of the wind turbine
$x_{ij,b}$	the reactance of the branch b connecting the ith and jth buses
α	scale and shape parameters of Beta function
Variables and Functions	
$f_v(v)$	weibull PDF of wind speed
$f_s(S)$	beta distribution function of S
μ^t	the mean deviation at the tth time interval
$AEL_{T,DG}$	the total annual economic loss with DG
$AEL_{T,noDG}$	the total annual economic loss without DG
CRF	the capital recovery factor
OF_1	the objective function representing the active total power losses
OF_2	the objective function representing total voltage drop
OF_3	the objective function representing the overall voltage stability index
OF_4	the objective function representing the total annual economic savings
$OVSI$	the overall voltage stability index
$P_{DG,m}$	the active power output of mth DG
P_{DGi}, $Q_{DG,m}$	the active and reactive power injected by ith DG
$PF_{DG,m}$	the power factor of mth DG
$P_{ij,b}$	the active power flow from ith bus to jth bus
$P_{ij,b}$	the active power flow from ith bus to jth bus
$Ploss$	the total network active power loss
$P_{loss,b}$	the active power loss of branch bth
$P_{loss,b}$, $Q_{loss,b}$	the active and reactive power loss of branch bth
P_{PVg}	the power generation of the photovoltaic unit
P_{slack}, , Q_{slack}	the active and reactive power injected by the slack bus
P_{WTg}	the power generation of the wind turbine
$Q_{DG,m}$	the reactive power output of mth DG
$Q_{ij,b}$	the reactive power flow from ith bus to jth bus
$Q_{ij,b}$	the reactive power flow from ith bus to jth bus

r	random number uniformly distributed on [0, 1].
v_w	the wind speed at the hub height of the WT
S	the solar irradiance on the PV module surface
S_b	the apparent power flow through bth branch
$S_{DG,m}$	the apparent power output of mth DG
$TAES$	the total annual energy saving
VD_T	the total system voltage drop
VD_T	the total system voltage drop
V_i	the voltage magnitude at bus i
V_j	the voltage magnitude at bus j
$VSI\,(i)$	the voltage stability index of bus i
$VSI\,(i)$	the voltage stability index of bus i
$VSI\,(j)$	the voltage stability index of bus j
$VSI\,(j)$	the voltage stability index of bus j
Γ	gamma function
θ_i	the phase angle at bus i
θ_j	the phase angle at bus j
σ^t	standard deviation at the tth time
S_g^t	gth state of solar irradiance at the tth time interval.

I. INTRODUCTION

Worldwide, rapidly increasing electricity demand and load expansion requirements need efficient power planning, and renewable energy sources utilization plays a crucial role to enhance the hosting capacity of the power system economically [1]. Currently, the major part of power generation (∼75%) is producing by fossil fuel-based generators such as gas, and micro-turbines [2]. However, the expected shortage in fossil fuels due to a substantial decrease in their natural backup [3] and the rapid increase of its price in the forthcoming years [4]. In addition, conventional resources produce massive carbon emissions [5]. Also, the power generated by large power plants located at a long distance from load centers, which is usually lost about 15% of active power in power transmission and distribution lines. The long distance and heavy loaded conventional distribution systems severely affect the efficiency of the power system in terms of higher power losses, weak voltage profile, as well as network stability and reliability issues [6].

Renewable energy based DG units [7] (such as wind turbine (WT), photovoltaic (PV) and micro-hydro generators) beside energy efficiency [8] have been recognized worldwide as an efficient pathway to avoid the issues related to conventional energy sources. Besides, the concept of microgrid has been also perceived as promising solution to the optimal use of energy resources [9] and for enhancing the resilience of power distribution systems [10].

Optimal integration and planning of RE-DG units in distribution network require to transfer paradigm of the system from passive to active, consequently resulting in the active distribution system (ADS) [11]. However, the inappropriate expansion and high penetration of RE-DGs into the distribution system is associated with possible operational and risk impacts that may compromise on system performance [12]. Also, the power generation of RE sources is strongly correlated to the weather, temperature, time and site location [13]. Therefore, the integration of RE-DG units into distribution systems such as WT and PV sources necessitates proper planning framework to ensure that the performance of distribution network can meet the expected power supply quality, system voltage stability, real power loss reduction, service reliability and economic profitability [14].

The potential benefits, challenges and progress of RE-DGs and their operational scheduling in electrical grids have been thoroughly investigated in the literature. Authors of [15] demonstrated the advancement from introducing an ADS regarding objective functions, system modeling, solution algorithms, and tools. In reference [16], a systematic review and tweet analysis on the advancement of RESs and corresponding major barrier to the acceptance of RE technologies are presented. The authors in [17], provided a comprehensive survey of different types of DG units and investigation of the newly emerging challenges such as settings of protection devices and power quality issues, and uncertain power generation associated with PV and WT sources. Based on international experience, the authors in [18] offered a detailed literature review on the impacts of RE-DGs on the planning and operation of the power system within the context of DG type, level of penetration and size, DG capacity and market structure of the electrical grid. Similar study is conducted by [19], however the authors put forwards the criteria for classification of DG and the planning objectives of both conventional and RE-DG units integration. The authors in [20] outlined the uncertainty modeling methods applied for accurate modelling of the stochastic behaviors and uncertain parameters correlated with RE-DGs. The authors in [21], discussed the major economic factors and technical management and power quality correction by which the operation of traditional distribution network is evolved to ADS. They also highlighted the modeling and control developments for the optimal operation of ADSs. In [9] provides a bi-level optimization scheduling for decision making of distribution system operator and reconfigurable multi-microgrid distribution systems in order to minimize the total system cost and maximize the profit for each microgrid. On the same way, in references [10] presented comprehensive resilience improvement planning framework for power-water distribution network with with multiple microgrids in order to minimize the expected inaccessibility value of loads to power and water against hurricanes as well as the investment cost considering uncertain parameters.The authors in [22] put in focus the pure economics of (i.e. financial viability, social costs and benefits) of DG integration in distribution systems. Also, the authors in [23] justified the environmental-wide aspects (i.e. the substantially reduction in greenhouse gas emissions, the public concerns over human health risks) of DG technologies. Fig. 1, gives a description of the acquired benefits of optimal planning of DG units.

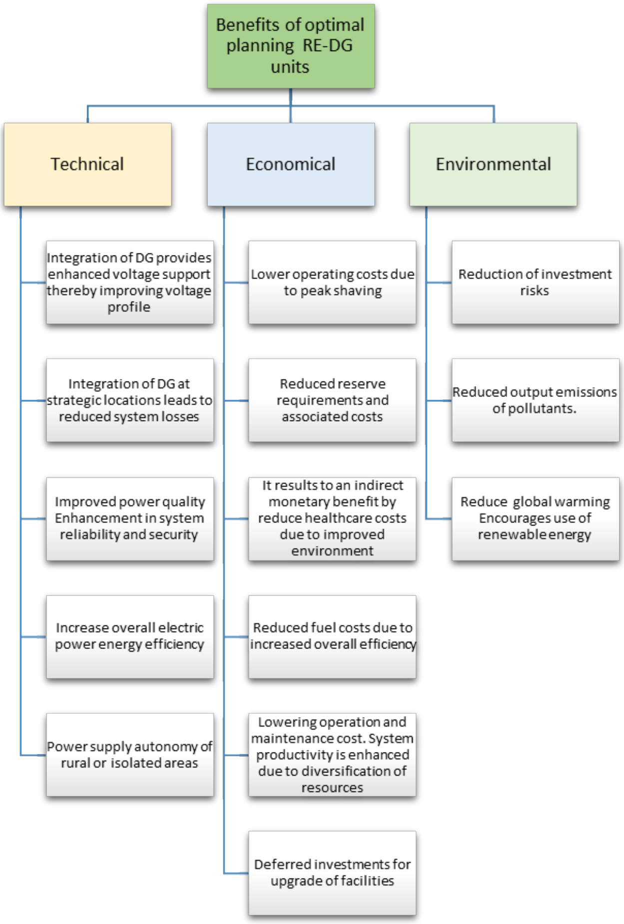

FIGURE 1. **Benefits of RE-DG units planning optimization.**

Recently, a number of researchers suggested different optimization methods to formulate the planning problem of RE-DGs in the distribution system. The optimal planning of RES-DG units in distribution networks has been addressed and numerous algorithms based on optimization techniques. BSOA methodology is reported for planning optimization of distribution systems to reduce the distribution network real loss and improve the voltage profile [24]. The authors also applied fuzzy expert rules or the initial identifications of RE-DG's location. The same objectives are considered by [26], while a new nature-inspired algorithm called WOA, is proposed for optimal planning of unity PF and 0.9 PF DG types and applied for IEEE 15-bus, 33-bus, 69-bus, 85-bus and 118-bus test systems. The potential solution of optimal allocation of single anf mutilpe RE-DGs units is presented in [29]. The authors used MINLP for primary objective of loss reduction with better optimal solution in reasonably less computational time in comparsion with other analytical and meta-heuristic methods. To minimize the total line losse, IWD algorithm is developed by [30] for optimal sizing of DG, while LSF method is involved for optimla installation of DG units. SKHA is suggested by [31] for the solution of optimal placement and capacities of single and multiple PV and WT generators in RDS to minimize the active power losses. Benefits of DGs integration in distribution system have evaluated, and dragonfly algorithm (DA) is presented in [32]. Also, the authors in [33], proposed a new technique named (MOEA/D) for optimal placement of RE-DGs, where active and reactive power loss minimization is considered as a primary objective. In [34], FA-based meta-heuristic method is presented to allocate the RE-DGs while reducing the power loss of both IEEE-33 and IEEE-69 bus system. The authors in [35] applied HGWO to find the potential solution of DGs placement problem where primary outcomes reveal technical benefit related to the distribution system. The authors in [36] used analytical technique based on LSF method to determine the best location of RE-DGs, while SA is used to calculate the optimal capacities of the RE-DGs that needs to be integrated into the power network for active power loss minimization. New hybrid method using GA-PSO is developed by [37] to evaluate the effect of DGs positioning into distribution system, while QOTLBO is suggested by [38]. In [39], IDSA is presened to to optimlally allocate the DGs and make the system perform better in term of power loss reduction. Hybrid algorithm using CS and GA is suggested by [40] to solve the planning problem of distribution networks. The optimal placement of RE-DGs PSO is used by [41] to obtain the optimal place and size of WT in IEEE 69-bus distribution system to minimize the microgrid power loss and maximization of the microgrid loadability maximize the load ability. Similar work is presented by [42]. The authors aims to find both optimal placement and power factor of different types of DGs while the objective function was to minimize the power distribution loss. The authors in [43] employs MTLBO technique to find the best sites to connect DG systems in a IEEE 33-bus and IEEE 69-bus distribution networks. Mutil-objective optimization problem is solved using a new algorithm, named (MOCD) to avoid premature convergence [25]. ABC algorithm is used in [27] for optimal DG's size, site, and power factor for minimzing total system active power loss. The authors in [28] have considered a multi-objective function (i.e. real power loss reduction, voltage profile improvement and to consolidate the system stability) for determining the best location and size of multi-type distributed DG units. BSA technique is utilized as the main problem solver, while fuzzy decision maker is applied to assort the preliminary buses for DG allocation 33- and 94- RDSs with different scenarios. Also, the authors of [44] presents an efficient multi-objective optimization approach based on BB-BC for optimal planning of dispatchable DGs and verified their algorithm on IEEE 69-bus and IEEE 123-bus distribution test systems. In [45], LSF method is used to identify the optimal locations for installation of DG units, while BFOA is used to find the optimal size of DG units with various load models at different load level. Also, the authors in [46] suggested a novel KHA approach for optimal siting of DGs in 33-bus, 69-bus and 118-bus RDSs to minimize the active power loss and energy loss of RDS's lines while keeping bus voltage and VSI within allowable margin. The authors show the ability of KHA for better quality solutions compared to stochastic search techniques.

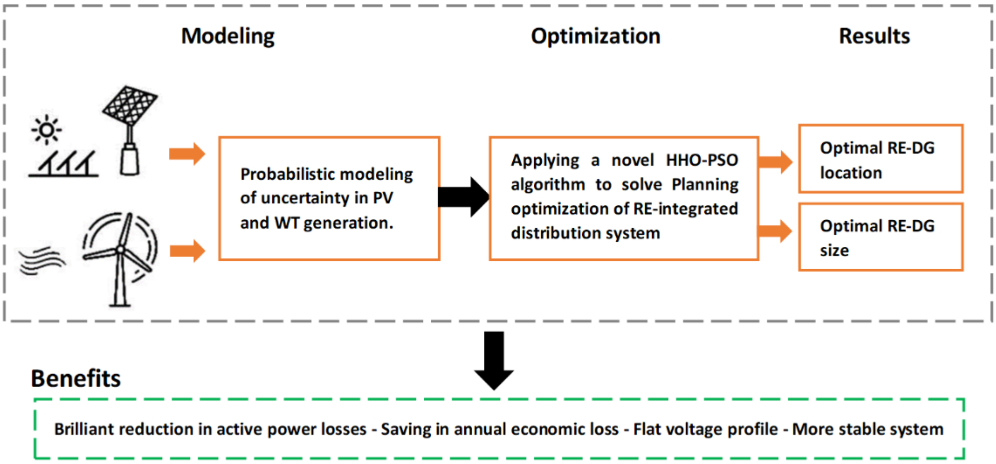

FIGURE 2. A diagram showing the steps of the current research work.

All these algorithms are presented and implemented on different distribution systems with different objective functions for the optimal planning of RE-DG units (i.e. proper allocation and sizing), while improving the system performance. Most of these works are focused on strengthening the technical indices of the distribution network in terms of power loss minimization and voltage profile improvement.

According to the diagram illustrated in Fig. 2 that shows the followed framework for efficient planning of RE-integrated distribution systems, the key contributions of this paper are:

- Novel HHO-PSO meta-heuristic technique is developed for solving the problem of optimal planning of RE-DG units that consider WT and PV generators.
- Formulation of planning problem considers PV and WT power generators, in which the stochastic nature of solar and wind resources is modeled using appropriate probability density functions (PDFs).
- The HHO-PSO method is implemented to maximize the techno-economic benefits of RESs integration into the power distribution system. To achieve that, minimizing active power loss and yearly economic loss as well as improving busses voltage and voltage stability indices are incorporated in the objective function.
- Different scenarios of PV and WT penetration, including single and multiple units are examined on two standard test systems; IEEE 33-bus and IEEE 69-bus; and 94-bus Portuguese real distribution system and results are compared with the existing literature.
- The Hybrid-PPSO-GSA approach outperforms all the other methods in terms of optimality of the solution, thus revealing that the solution is a globally optimal one.

The rest of the paper is structured as follows: modeling of the stochastic behavior of WT and PV is expressed in section II. Section III presents the problem formulation, while the solution approach and proposed methodology are described in section IV. Implementation and validation of proposed HHO-PSO and detailed simulation results along with the comparison study with literarure are presented in section V. Finally, the work done is concluded in section VI.

II. MODELING OF STOCHASTIC BEHAVIOR OF RENEWABLE ENERGY SOURCES

The output power of renewable energy sources is dependable on external condition (i.e., solar irradiance, temperature, wind speed), and it is necessary to consider the uncertainty and stochastic behaviour of RE output power while solving the planning optimization of RE-DG units in the power system. The realistic modeling of RE sources makes better decisions in the optimal planning of RE-DGs in distribution system. Probabilistic MCS method is the most common to characterize and dealt with the power system uncertainties [47]. In this sense, the uncertainties related to wind speed and solar irradiance were implemented by describing them using probability PDFs [48].

From the literature, two PDFs named; Weibull and Beta functions are usually recommended and utilized to model stochastic nature wind speed and solar irradiance, respectively [47]. In this work, the historical data of weather data for one year (between the period from 2017 to 2018), where the hourly values are collected at the place under study the entire period from olar and meteorological data sets from NASA.The acquired data are used to obtain a typically annual stochastic profile of the solar irradiance and wind speed measurements. The modeling of WT and PV is explained in the following sub-section as in [49].

A. MODELLING OF WIND TURBINE

The power generation of a wind turbine, at specific wind speed, can be expressed as:

$$P_{WT}\left(v_w\right)=\begin{cases}0 & \textit{for } v_w \leq v_i\\ \left[(v_w-v_i)/(v_r-v_o)\right]\times P_{wtr} & \textit{for } v_i<v_w\leq v_n\\ P_{WTr} & \textit{for } v_n<v_w\leq v_o\\ 0 & \textit{for } v_w\geq v_o\end{cases} \tag{1}$$

Using Weibull PDF, the stochastic behavior of wind resources at a certain location can be drive as:

$$f_v(v) = K/C \times (v/C)^{K-1} \times e^{-(v/C)^K} \quad (2)$$

The CDF of Weibull function is given by (3) whereas its inverse is used to calculate the wind speed as in (4).

$$F_v(v) = 1 - e^{-(v/C)^K} \quad (3)$$

$$v = C \times [-\ln(r)]^{(1/K)} \quad (4)$$

The estimated values of the shape factors C and k are calculated based on the values of the mean and standard deviation of the measurements of the wind speed in the considered time period (t) using (5) and (6).

$$k^t = \left(\sigma_v^t/\mu_v^t\right)^{-1.086} \quad (5)$$

$$C^t = \mu_v^t/\Gamma\left(1 + 1/K^t\right) \quad (6)$$

Moreover, to comprehend the Weibull PDF in discrete form, the considered time interval is further sub-divided into a number of Ns states. Thus, taking into account (g=1÷Ns), the equation (2) and (5) can be used to determine the wind speed and its probability in each state. So, the forecasted WT output power for a specified time value of t can be determined as follow:

$$P_{WT} = \left[\sum_{g=1}^{N_v} P_{WTg} \times f_v\left(v_g^t\right)\right] / \left[\sum_{g=1}^{N_v} f_v\left(v_g^t\right)\right] \quad (7)$$

where, P_{WTg} is calculated via equation (1) and $v = v_g^t f_v\left(v_g^t\right)$ is the wind speed probability for the gth state and tth time interval.

B. MODELLING OF PHOTOVLTAIC

A photovoltaic unit generates electrical power based on solar irradiance:

$$P_{PV}(G) = \begin{cases} (P_{PVr} \times G^2)/(G_{STC} \times R) & for\ G < R_c \\ (P_{PVr} \times G)/G_{STC} & for\ G > R_c \end{cases} \quad (8)$$

Taking into account the uncertainty of solar irradiance, the Beta PDF is used to get better modeling of PV unit:

$$f_s(G) = \begin{cases} [\Gamma(\alpha+\beta)/(\Gamma(\alpha) \times \Gamma(\beta))] \times G^{(\alpha+1)} \\ \times (1-G)^{(\beta-1)} \\ \quad for\ 0 \le G \le 1,\ \alpha \ge 0,\ \beta \ge 0 \\ 0 \\ \quad otherwise \end{cases} \quad (9)$$

The shape factors α and β of the Beta function determined using the mean and standard deviation of the measured solar irradiance data in a time period (t) as follows:

$$\beta^t = \left(1 - \mu_G^t\right) \times \left[\left(\mu_G^t \times (1 + \mu_G^t)/(\sigma_G^t)^2\right) - 1\right] \quad (10)$$

$$\alpha^t = (\mu_G^t \times \beta^t)/(1 - \mu_G^t) \quad (11)$$

For the realization of Beta PDF in a discrete pattern, the time interval (t) is further sub-divided into Ns slots. Hence considering (g=1÷Ns) the equation (9) can be used to calculate solar irradiance and probability, furthermore taking into account the solar irradiance and probability in a specific interval the forecasted output power of photovoltaic is expressed as:

$$P_{PV} = \left[\sum_{g=1}^{N_s} P_{PVg} \times f_s\left(S_g^t\right)\right] / \left[\sum_{g=1}^{N_s} f_s\left(S_g^t\right)\right] \quad (12)$$

The power generated by the wind turbine PPVg is determined via equation (8), where $G = G_g^t$ and $f_s\left(G_g^t\right)$ is the solar irradiance probability for the gth state during the specific tth time interval.

III. PROBLEM FORMULATION

The integration of RESs in distribution networks makes the RE-DGs units planning problem more complicated due to the stochastic and intermittent nature of renewable resources [50]. The planning problem of RE-DGs can be considered as a constrained, non-linear, discrete optimization problem [35]. The problem is formulated as an optimal power flow model [28], which has a single or multi-objective optimization function. The considered objectives should be properly optimized while satisfying the system operational constraints.

A. OBJECTIVE FUNCTION

The main objective of this study is to maximize the techno-economic benefits by the integration of RE-DG unit into distribution networks. Several performance indicators and practical assumptions should be taken into account while solving the planning problem of RE-DGs. Therefore, minimizing active power losses, optimizing the annual profit as well as improving voltage and voltage stability index of system buses are considered as main objectives of this study. This multi-objective function can be expressed via a weighted sum method.

$$\begin{aligned} OF_T &= \min F(X, U) \\ &= \min(\omega_1 \times OF_1 + \omega_2 \times OF_2 + \omega_3 \times OF_3 + \omega_4 \times OF_4) \end{aligned} \quad (13)$$

where, OF_1, OF_2, OF_3, and OF_4 represents the reduction of the total active power losses, improvement of buses voltage, strengthening of buses *VSI*, and saving in yearly economic loss, respectively. Also, ω_1, ω_2, ω_3, and ω_4 are weighting factors, in which the total sum of absolute values of the weights associated with each objective should equal to 1.0. It is pertinent to mention that the values of the decision criteria mentioned in equation (13); are calculated using per unit values. The four studied objectives can be expressed mathematically as follows [6]–[49]:

$$OF_1 = Ploss = \sum_{b=1}^{NBR} P_{loss,b} \quad (14)$$

$$P_{loss,b} = g_{ij,b} \times \left[V_i^2 + V_j^2 - 2 \times V_i \times V_j \times \cos\left(\theta_i - \theta_j\right)\right] \quad (15)$$

$$OF_2 = VD_T = \sum_{i=1}^{NB} \left| V_i - V_i^{ref} \right| \tag{16}$$

$$OF_3 = 1/OVSI = 1/\sum_{i=2}^{NB} |VSI(j)| \tag{17}$$

$$VSI(j) = |V(i)|^4 - 4 \times [P_{ij,b} \times x_{ij,b} - Q_{ij,b} \times r_{ij,b}]^2 - 4 \times [P_{j,b} \times r_{ij,b} + Q_{ij,b} \times x_{ij,b}] \times |V(i)|^2 \tag{18}$$

$$OF_4 = TAES = AEL_{T,noDG} - AEL_{T,DG} \tag{19}$$

$$AEL_{T,noDG} = Ploss_{noDG} \times C_E \times 8760 \tag{20}$$

$$AEL_{T,DG} = Ploss_{RES-DG} \times C_E \times 8760 + \left[\left(C_{DG} \times \sum_{m=1}^{NDG} P_{DG,m} \right) / CRF \right] \tag{21}$$

$$CRF = \left[r \times (1+r)^{T_{DG}} \right] / \left[(1+r)^{T_{DG}} - 1 \right] \tag{22}$$

B. EQUALITY AND INEQUALITY CONSTRAINTS

A set of equality and inequality constraints that include power flow in the system, must be satisfied while solving the the proposed objective function.

- The mathematical formulation of the power balance in the power network can be expressed as follows:

$$P_{slak} + \sum_{m=1}^{NDG} P_{DG,m} = \sum_{i=1}^{NB} P_{D,i} + \sum_{b=1}^{NBR} P_{Loss,b} \tag{23}$$

$$Q_{slak} + \sum_{m=1}^{NDG} Q_{DG,m} = \sum_{l=1}^{NB} Q_{D,l} + \sum_{b=1}^{NBR} Q_{Loss,b} \tag{24}$$

- The voltage extent at each bus must be kept within specified (standard) limits to a high-quality power supply.

$$V\min \leq V_i \leq \max i \quad \forall NB \tag{25}$$

- The apparent power flow through any branch in the network must be less than its thermal limit:

$$S_b \leq S_b^{\max} b \quad \forall NBR \tag{26}$$

- The DG capacity constraints are related to the maximum installed capacity of all DG units; i.e. DG penetration level and the maximum size of individual units. Also, the DG power factor should be within allowable limits:

$$\sum_{m=1}^{NDG} S_{DG,m} \leq \mu \times \sum_{i=1}^{NB} S_{D,i} \tag{27}$$

$$S_{DG,m} \leq S_{DG,m}^{\max} m \quad \forall NDG \tag{28}$$

$$PF_{DG,m}^{\min} \leq PF_{DG,m} \leq PF_{DG,m}^{\max} \tag{29}$$

where,

$$S_{DG,m} = \sqrt{P_{DG,m}^2 - Q_{DG,m}^2} \tag{30}$$

$$S_{D,i} = \sqrt{P_{D,i}^2 - Q_{D,i}^2} \tag{31}$$

To avoid back power flow through the main substation, the coefficient μ is usually identified in the range (0.4 - 1) [51].

IV. METHODS

In this section, we will illustrate the detailed steps of the Harris Hawks Optimizer (HHO) and Particle swarm Optimization (PSO). Then, the proposed method based on a modified version of HHO using the PSO operators to solve the problem of optimal planning of RES-DG units in radial distribution networks.

A. HARRIS HAWKS OPTIMIZER (HHO)

The Harris Hawks optimization (HHO) is a population-based method which simulate the behaviors of the Harris Hawks to catch the rabbits.

Similar to other population-based methods, the HHO consists of a set of steps starting by generating a set of random solutions (X) then computing the fitness value for each of them. The next step is to determine the best fitness value and the corresponding solution which called best solution (X_b). Thereafter, HHO uses its operators either in exploration or exploitation to update the current solution. For example, in exploration phase, the solution is updated using the following equation.

$$X(t+1) = \begin{cases} X_r(t) - r_1 \times |X_r(t) - 2 \times r_2 \times X_r(t)| \\ \quad for\ q \geq 0.5 \\ X_b(t) - X_m(t) - r_3 \times |lb + r_4 \times (ub - lb)| \\ \quad otherwise \end{cases} \tag{32}$$

where, X_m, and X_r represents the average of population, and random solution, respectively, at iteration t. The r_1, r_2, r_3, r_4, q represents random values generated from [0, 1], in addition, the q is used to make the HHO depends either of random solution the first branch in Eq. (30) or on X_m and X_b (i.e., the second branch). The next step is to change the states of HHO from exploration to exploitation by using the following equation:

$$E = 2 \times E_0 \times (1 - t/T) \tag{33}$$

where, $E_0 \in [-1, 1]$ represents the initial value of the escaping energy of the rabbit (E). Moreover, T represents the total number of iterations. When the value of |E| ≥ 1 then the solution will explore the search domain, move to the exploitation phase.

In the exploitation phase, the solutions can use one of the following four strategies; 1) Soft besiege, 2) Hard besiege, 3) Soft besiege with progressive rapid dives, and 4) Hard besiege with progressive rapid dives. The soft besiege is formulated as follows:

$$X_r(t+1) = \Delta X(t) - E \times |J \times X_b(t) - X(t)|, \quad \Delta X(t) = \Delta X_b(t), \quad J = 2 \times (1 - r_5) \tag{34}$$

where, J is the random jump strength of the rabbit and $r_s \in [0, 1]$is a random value. This strategy is used if $|E| \geq 0.5$

Algorithm 1 HHO

Inputs: Determine the number of solutions N, and maximum number of iteration T
Outputs: The best solution X_b
Generate the initial solutions X_i ($i = 1, 2, 3, \ldots., N$)
Repeat
Evaluate the quality of each solution using the fitness values
Determine the best solution X_b
for $i = 1$:N
Update the value E by Eq. (33)
If ($|E| \geq 1$)
Update X_i using Eq. (32)
If ($|E| < 1$)
If($r \geq 0.5$ and $|E| \geq 0.5$)
Update X_i using Eq. (34)
Else if ($r \geq 0.5$ and $|E| < 0.5$)
Update X_i using Eq. (35)
else if ($r < 0.5$ and $|E| \geq 0.5$)
Update X_i using Eq. (36)
else if($r < 0.5$ and $|E| < 0.5$)
Update X_i using Eq. (39)
Until (terminating state is not occurred)

and $r \geq 1$, where r is probability of the rabbit to escape. Meanwhile, the hard besiege is formulated using Eq. (35) and used when $|E| \geq 0.5$ and $r \geq 0.5$.

$$X_r(t+1) = X_b(t) - E \times |\Delta X(t)| \tag{35}$$

In the case of $|E| \geq 0.5$ and $r < 0.5$, then the Soft besiege with progressive rapid dives is used which formulated using the following equation:

$$X(t+1) = \begin{cases} Y & if\ Fit\ (Y) < X(t) \\ Z & if\ Fit\ (Z) < X(t) \end{cases} \tag{36}$$

where, Y is the current movement which represented by:

$$Y = X_b(t) - E \times |J \times X_b(t) - X(t)| \tag{37}$$

In addition, Z represents the rapid dives of the hawks when Y is not good and this simulated using Eq. (38), which depends on the levy flight ($levy$).

$$Z = Y + S \times levy(D) \tag{38}$$

where, D is the dimension of the current solution and $S \in R^{1\times D}$ represents a random vector.

The hard besiege with progressive rapid dives is used when $|E| < 0.5$ and r < 0.5 and this formulated as:

$$X(t+1) = \begin{cases} Y & if\ Fit\ (Y) < X(t) \\ Z & if\ Fit\ (Z) < X(t), \end{cases}$$
$$Y = X_b(t) - E \times |J \times X_b(t) - X_m(t)| \tag{39}$$

where Z is given in Eq. (38).

The steps of HHO are given in Algorithm (1).

Algorithm 2 PSO

Inputs: Generate an initial random population with size N and PSO parameters (v, c_1, c_2 and w)
Outputs: The best solution X_b
Repeat
Compute the fitness value for each particle.
Determine the global best solution (X_g) and the personal best solution (X_b)
Update the velocity of each solution using Eq. (40).
Update the position of each solution using Eq. (41).
Until (stop conditions)

B. PARTICLE SWARM OPTIMIZATION (PSO)

In this section, the basic information of the particle swarm optimization (PSO) algorithm is introduced. In general, the PSO simulates the social-behaviors birds or fish and it is considered as population-based method. The PSO depends on updating the velocity and position of each particle to find the solution.

The PSO starts by using a set of N random particles which represent the solution of the given problem. The next step is calculating the fitness value for each particle is computed, then find the best solution. Thereafter, the velocity of each particle (v_i) is updated using the following:

$$v_i(t+1) = w \times v_i(t) + C_1 \times rand\left(X_i^{best} - X_i(t)\right) + C_2 \times rand\left(X^{gbest} - X_i(t)\right) \tag{40}$$

where, X^{gbest} represents the global best solution, X_i^{best} is the best solution for the current solution, and c_1 and c_2 are the best local and global position weight coefficient, respectively, and w represents the inertia coefficient which controls the influence of the previous velocity on the updated velocity.

The X_i is the position of the particle that will be updated using the following equation:

$$X_i(t+1) = X_i(t) + v_1 \times (t+1) \tag{41}$$

The steps of PSO are summarized in Algorithm (2).

C. PROPOSED HHO-PSO SOLUTION METHOD

In this section, the improved of HHO, called HHO-PSO, is introduced to solve the problem of optimal sitting and sizing of RES-DG units in distribution systems. Because of the traditional HHO has high ability to exploitation the search space, its exploration ability needs more improvements. Therefore, we used the PSO to achieve this improvement based on the ability of PSO for fast exploration of the available search space. Accordingly, the main aim of HHO-PSO is to solve the problem optimally while enhancing the convergence of the standard HHO using the PSO.

In this regards, the RE-DG optimal sitting and sizing can be expressed and encoded mathematically as follows:

$$\min F(X, U)$$
$$\text{S.t. } g(X, U) = 0 \ \&\ h(X, U) \leq 0 \tag{42}$$

Algorithm 3 HHO-PSO

Inputs: Initialize a set of N solutions with dimension D, parameters of HHO and PSO.
Outputs: The best solution X_b.
Generate the initial solutions X_i $(i = 1, 2, 3, ..., N)$
Repeat
Compute the fitness value for each solution.
Determine the smallest fitness value and its corresponding solution.
for $i = 1{:}N$
Compute the probability of the fitness value ($Prob_i$) using (13) and (45).
If $Prob_i \geq 0.5$
Using the operators of HHO as descripted in *Algorithm 1*
Else
Using the operators of PSO as descripted in *Algorithm 2*
End
End for i
Until (T < maximum number of iterations)

where, F is the wighted objective function to be minimized as givn in equation (13), while g and h are the vectors of the control and dependent (or state) variables, respectively. The control variables represents the DG(s) candidate location(s), size(s) and PF of DG of WT type and only DG(s) size and candidate location(s) for DG of PV type.

$$X = [L_1^{DG} \ldots L_{NB}^{DG}, S_1^{DG} \ldots S_{NDG}^{DG}, PF_1^{DG-WT}, \ldots PF_{NDG}^{DG-WT}] \quad (43)$$

The dependent variables are the power generated by the slack bus, voltage at load bus, and distribution line power flow.

$$U = [SG_{slack}, V_1^{Bus} \ldots V_{NB}^{Bus}, S_1^{branch}, \ldots S_{NBR}^{branch}] \quad (44)$$

In HHO-PSO population has a set of N chromosomes that represent candidate solutions X; each chromosome has a set of properties which can be mutated and altered and it can be encoded in binary as strings of 0 and 1. Also it can be represented using real and decimal codifications.

To optimize the planning of RE-integrated distribution system, the information showing the optimal sitting and sizing of RE-DG units should be encoded in the genes of chromosome. The structure of the proposed chromosome is composed of three parts. The first part determine installation of RE-DGs on system buses (i.e. the candidate locations). The integer values of the genes in this part are from 1 to the maximum number of system buses and its interval is between 1 to the maximum number of installed DG units on buses. The genes of second part shows the power generation of RE-DGs in the considered load level, and its genes have real values between 0 and the related RE-DG's capacity. In the third part of the proposed chromosome, each gene gets a real values from 0 to 1, and represents the optimal power factor of the installed WT-DG units. However, the values of that genes are always 1 when the installed DG units are PV type. The number of genes in this part is equal to the maximum number of the installed DG units.

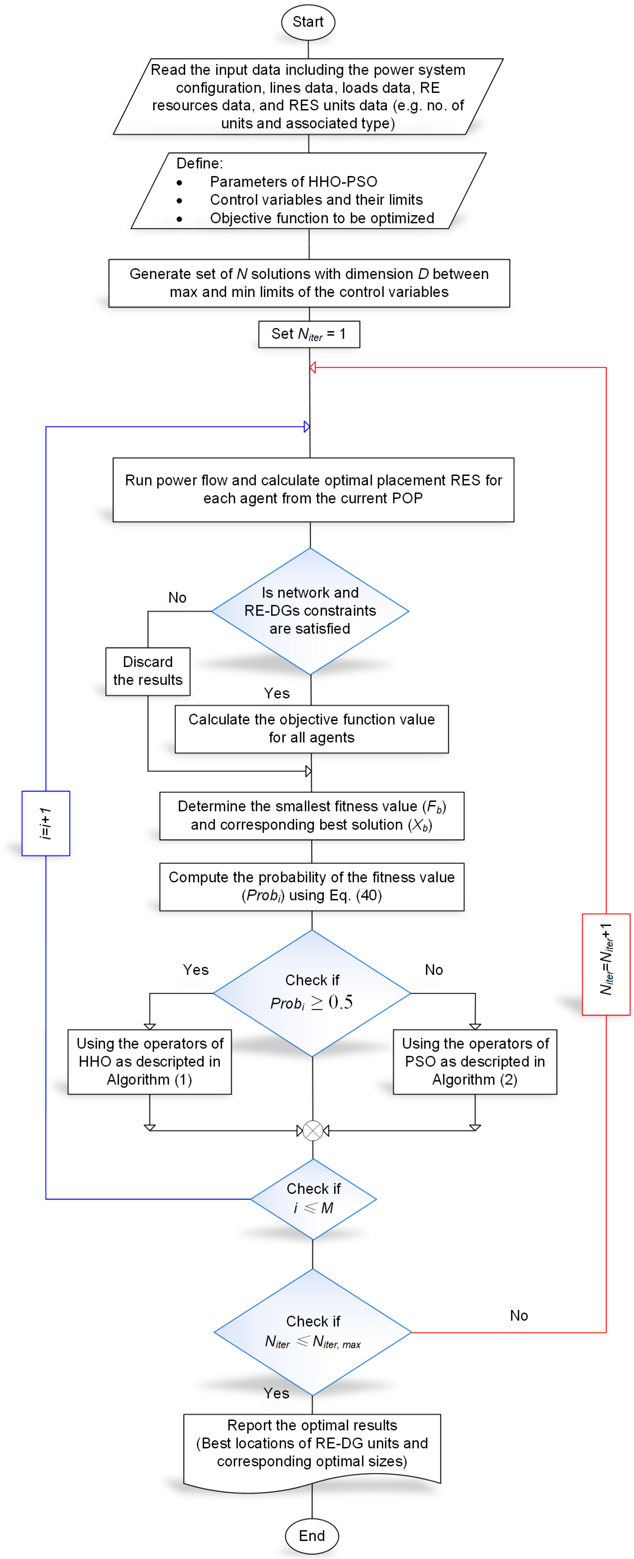

FIGURE 3. Flow diagram of HHO-PSO implementation for optimal planning of RE-integrated distributions system.

The proposed algorithm starts by determining the initial value for the candidate solutions, then the fitness value for each solution is computed using equation (13). The next step

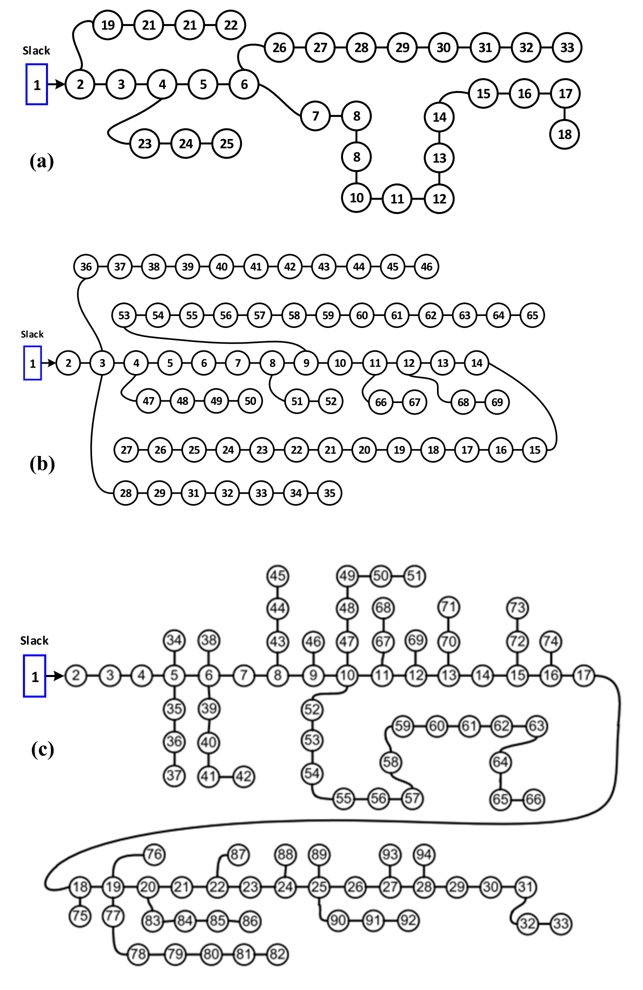

FIGURE 4. Considered RDSs, (a) IEEE 33 bus, (b) IEEE 69 bus, (c) Practical Portuguese 94 bus.

is to determine the best solution (X_b) which has the smallest fitness value (F_b) and then update the other solutions using it and the operators of the HHO and PSO. This updating process is performed by a set of steps which started by computing the probability of each candidate solution (X_i) according to its fitness value (Fit_i) as:

$$Prob_i = Fit_i / \sum_{i=1}^{N} Fit_i \tag{45}$$

In the case of the $Prob_i \geq 0.5$ then the operators of HHO will be used, otherwise the operators of PSO will be used to update the current candidate solution. The process of updating the solutions is performed until reached the stopping conditions; either a maximum number of populations has been achieved, or a satisfactory value for the fitness function has been obtained for the generation.

While solving the problem using the HHO-PSO, the execution of the proposed algorithm follows many steps and procedures that are given by the flow diagram illustrated in Fig. 3.

TABLE 1. Test systems specifications and initial power flow results without any RESs.

Item	33 bus system	69 bus system	94 bus system
System Specifications:			
NB	33	69	94
Nbr	32	68	93
Vsys (kV)	12.66	12.66	15
Base MVA	100	100	100
S_{load} (MVA)	3.715 + j2.300	3.802 + j2.694	4.797 + j 2.323
Intial power flow results:			
P_{loss} (kW)	210.84	224.930	362.86
Q_{loss} (kVAr)	143.03	102.176	504.04
V_{min},bus (p.u.)	0.9039,18	0.9102,65	0.5183 ,92
V_{max},bus (p.u.)*	0.9970,2	1.0,2	0.9804 ,2
VD_T (p.u)*	1.7002	1.8374	9.126
OVSI	25.842	61.207	62.265
$AEL_{T,noDG}$ *($)*	92409.240	98519.530	158932.68
CPU time (s)	3.477212	6.142094	6.831223

*Without slack bus.

TABLE 2. Input parameters used in the numircal simulation.

Item	Set value(s)
HHO-PSO parameters:	
$N_{iter,max}$	100
N_{pop}	50
N_{runs}	50
System inequality constraints:	
Bus voltage limits (p.u.)	±5%*
RE-DG size limits (MVA)	$0 \leq S_{DG} \leq 3$
RE-DG PF limits [24]	$1 \leq PF_{PV} \leq 1$ & $0.65 \leq PF_{WT} \leq 1$
Max. number of RES units per one bus	2
Cost data [25]***:***	
C_{DG} ($/kW)	30
T_{DG} (years)	10
C_E ($/kWh)	0.05
R (%)	10

*±10% for Portuguese 94 bus RDS

V. SIMULATION RESULTS AND DISCUSSIONS

In order to elucidate the features of the proposed HHO-PSO algorithm and examine its performance, three radial distribution systems (RDSs) are selected; standard IEEE 33-bus, standard IEEE 69-bus, and practical Portuguese 94-bus (RDSs). The line and load data of IEEE systems are obtained from [52], and the data of 94 bus practical distribution system has obtained from [53]. The load model of the distribution systems is assumed as a constant power load [54]. The one-line diagrams of the considered systems are shown in Fig. 4.

The proposed algorithm is coded using MATLAB 2018b [55] and simulations are carried out on a Dell PC of Intel®Processor CoreTM i7-8700 CPU clocked 3.20 GHz and 32.0GB of RAM. Backward/forward sweep algorithm [56], [57], whose convergence is robust and guaranteed [54], is employed to solve the power flow calculations. The system specifications and outcome of initial power flow results without introducing RESs and with 100% loading are depicted in Table 1 for the investigated RDSs.

A. SIMULATION STRATEGIES

The proposed HHO-PSO algorithm is applied to solve the problem of opimal planning of of renewable energy-integrated distribution system considering uncertainties of PV and WT output power. Different penetration levels (i.e., single and multiple units) of PV and WT units are simulated and analyzed. The PV inject active power only, while the WT has a capability of active and reactive power support. Also, it is assumed that only one RE-DG unit can be penetrated on the same bus. The primary goal of the optimization is to determine the optimal size and location of RESs to enhance the techno-economic performance of the distribution system, as described in section III.

The input data and cost parameters related to system budget for optimal planning problem are shown in Table 2. Two scenarios of RE-DGs integration, including single and multiple DGs, are examined to prove the positive impacts of optimal allocation of PV and WT on system performance. In addition, to verify the superiority and effectiveness of the proposed algorithm, results obtained by the HHO-PSO algorithm are evaluated by comparing with other optimization techniques reported in the literature.

B. CASE STUDY-1: IEEE 33 BUS RDS

The proposed HHO-PSO is implemented on the standard IEEE 33 bus test system, and different scenarios are examined (i.e., integration of single PV or WT DG unit). Moreover, the results of obtained by HHO-PSO are organized in Table 3. For both PV and WT generators, a significant reduction in active power loss has been reinforced. In addition, a noticeable improvement is achieved in voltage profile and system stability, as illustrated in Fig. 5 and Fig. 6, respectively.

In the first scenario, using the integration of single RE-DG unit, bus number 6 is suggested as the optimal location for PV and WT installation. The optimal size of PV 2574.3 kW and WT 3088.0 kVA with a power factor of 0.8239 The active power loss obtained by the proposed technique decreased to 103.944 kW and 61.359 kW by suggesting the PV and WT, respectively. Moreover, Fig. 7 shows the branch power loss variation with and base case without the integration of PV and WT units, where the current flow and power loss in branches 1 to 5 is decreased drastically after PV or WT unit's penetration. Optimal planning of PV and WT reduces the yearly economic loss to 45535.257 $ and 35882.887 $ from 92409.240 $ for the base case without RESs. Furthermore, the minimum value of voltage magnitude has improved to 0.9650 p.u. and 0.9668 p.u using PV and WT respectively, together with increasing the VSI of all system buses. Thus, strengthening system power quality and stability. It should be mentioned that the optimal planning of RE-DGs in active distribution network has off-line implementation nature; thus, the time of processing is not considered a concern [28]. Nevertheless, the HHO-PSO consumes a small value of 4.187685 sec and 4.142924 sec of CPU time with PV and WT, respectively.

In the second scenario, the integration of multiple RE-DG units (i.e., two and three units) is considered, and its implications are investigated. For the case of two PVs, buses 13 and 30 are selected as optimal locations for PV unit integration with a capacity of 846.0 kW and 1158.2 kW respectively. On the other hand, the optimal locations for three PV units are the buses 14, 24 and 30 and the PVs capacities are 761.4, 1094.7 and 1068.4 kW, respectively. It is worth mentioning that the active power loss has significantly reduced to 85.870 kW and 71.437 kW by two PV and three PV units, respectively. On the same line, the yearly savings enhanced to 54794.534 $ and 61116.390 $ are achieved with two PV and three PV units, respectively.

On the other side, while optimal planning of two WT units, buses 12 and 30 are designated as optimal locations with optimal WTs power capacities of 1064.9 kVA, 1504.6 kVA and with power factors equals 0.9042 and 0.7228 respectively. As a result, the network losses are minified to 28.579 kW. Also, the optimal integration of three WT units at buses 14, 24 and 30 provide intensively decreased the power loss to 11.659 kW by suggesting the sizes and corresponding power factors of WT units are 820.4/0.9137, 1173.8/0.8961 and 1481.4.3/0.7069 kVA/PF respectively. Moreover, the obtained results also show that the annual economic savings are increased to 79888.473 $ and 87299.341 $, respectively.

In general, due to capability of WTs to supply reactive power, it gives better voltage profile and noticeably enhance system stability compared to PV (realize Figs. 6 and 7), where the minimum values of bus voltages are achieved 0.9806 p.u. at bus 25 and 0.9930 p.u at bus 33., also the increase of 31.216 and 31.497 in the OVSI by the contribution of 2 and 3 WTs, respectively. Clearly, it can be seen from Table 3 that whenever the number of PVs and WTs (i.e., the penetration level of RESs) is increased, a considerable improvement in the techno-economic performance is achieved, which is presented by the bar graph given in Fig. 8. Table 7 arranges the numerical results of the proposed HHO-PSO method and comparison with other existing techniques reported in the literature for 33-bus RDS. The fair comparison shows that the proposed algorithm provides global optimal solutions and better results than other methods and verify the ability of HHO-PSO to solve the planning problem of RE-DG units in the distribution system and results to improve the system performance.

C. CASE STUDY-2: IEEE 69 BUS RDS

In this case, the proposed solution method is implemented on the standard IEEE 69 bus test system, along with different scenarios. The optimization results are gained using HHO-PSO for the embedding of single and multiple PV and WT unit(s) are summarized in Table 4. Also, the bus voltages and VSI profiles are illustrated in Fig. 9 and Fig. 10, respectively. The branch active power losses profile is presented in Fig. 11.

TABLE 3. Results of HHO-PSO for optimal allocation of RE-DG units (33 bus RDS).

Item	Single RE-DG		Multiple RE-DGs			
	PV	WT	2 PV	2 WT	3 PV	3 WT
P_{loss} (kW)	103.944	61.359	85.870	28.579	71.437	11.659
V_{min},bus (p.u.)	0.9510,18	0.9668,18	0.9685,33	0.9806,25	0.9688,33	0.9930,33
V_{max},bus (p.u.)	0.9986,2	1.0013,6	0.9983,2	1.001,30	0.9988,2	1.0017,30
RES size and location	2574.3/1,6	3088.0/0.8239,6	846.0/1,13 1158.2/1,30	1064.9/0.9042,12 1504.6/0.7228,30	761.4/1,14 1094.7 /1,24 1068.4/1,30	820.4/0.9137,14 1173.8/0.8961,24 1481.4/0.7069,30
OVSI	28.828	30.14	29.476	31.216	29.715	31.497
VD_T (p.u)	0.830	0.478	0.647	0.195	0.584	0.122
$AEL_{T,DG}$ *($)*	45535.257	35882.887	37613.706	12520.767	31292.850	5109.899
TAES ($)	46873.983	65526.353	54794.534	79888.473	61116.390	87299.341
CPU time (s)	4.187685	4.142924	4.200665	4.212267	4.294892	4.282258

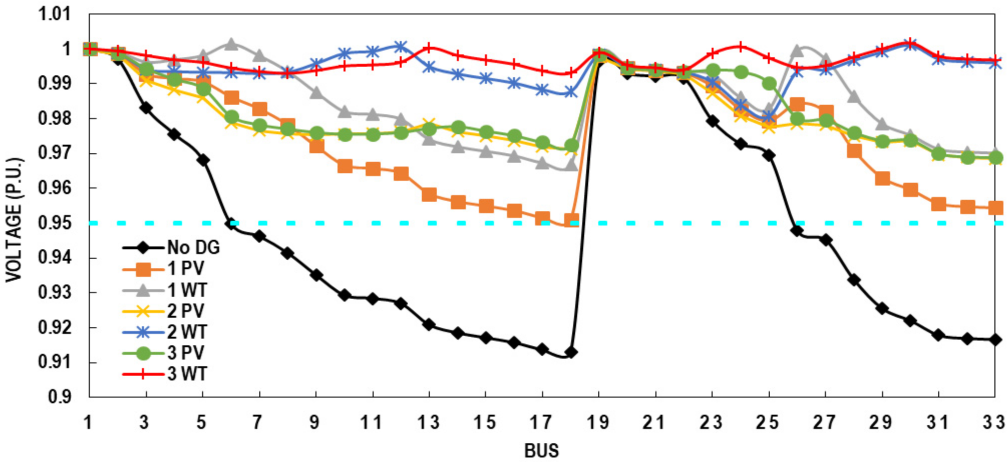

FIGURE 5. Voltage profile of 33 bus RDS without and with RE-DG unit(s).

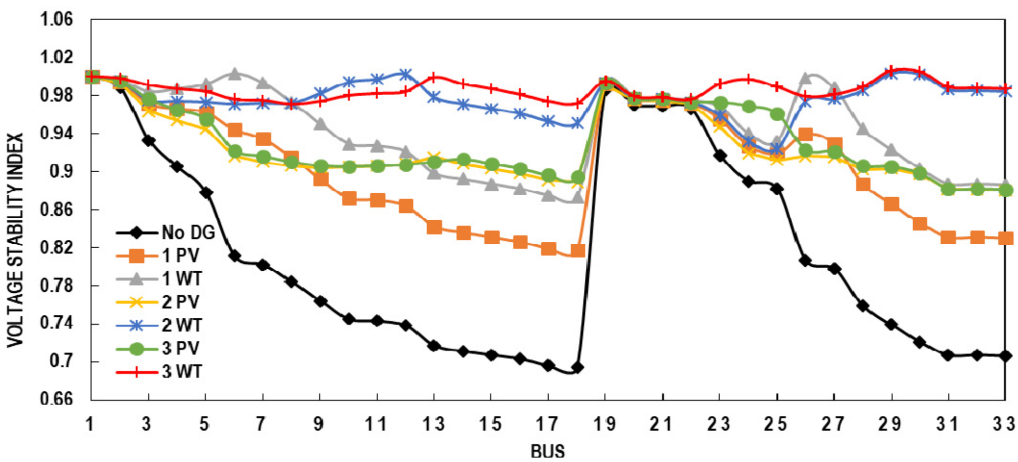

FIGURE 6. Bus VSI profile of 33 bus RDS without and with RE-DG unit(s).

In the first scenario, one RE-DG unit (PV or WT) integration is considered, bus 61 is nominated as the best location for installation of 1872.7 kW PV array. The optimal planning of the PV unit dramatically reduces the active power loss, improves the voltage profile and system stability such that the minimum voltage of buses is 0.9683 p.u and the OVSI is 64.611. The economic performance of the system has also improved by decreasing the annual loss cost to 36457.674

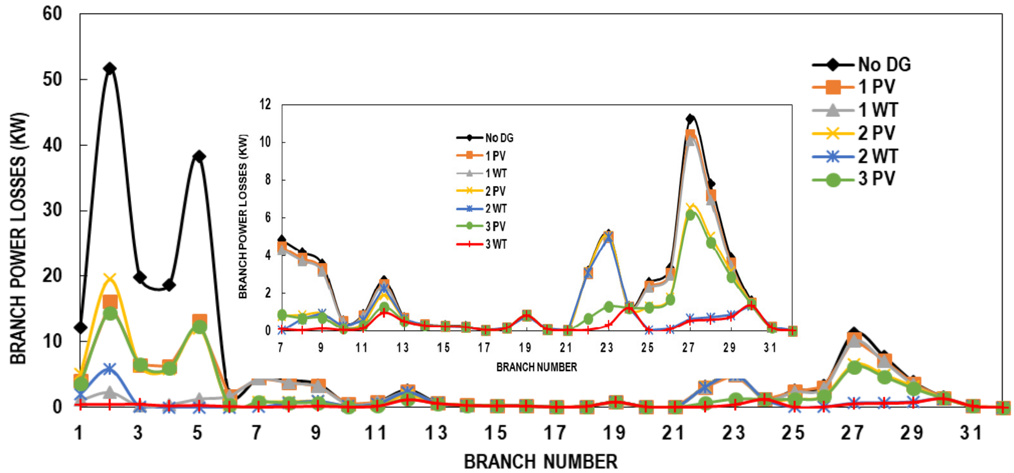

FIGURE 7. Branch active power loss profile of 33 bus RDS without and with RE-DG unit(s).

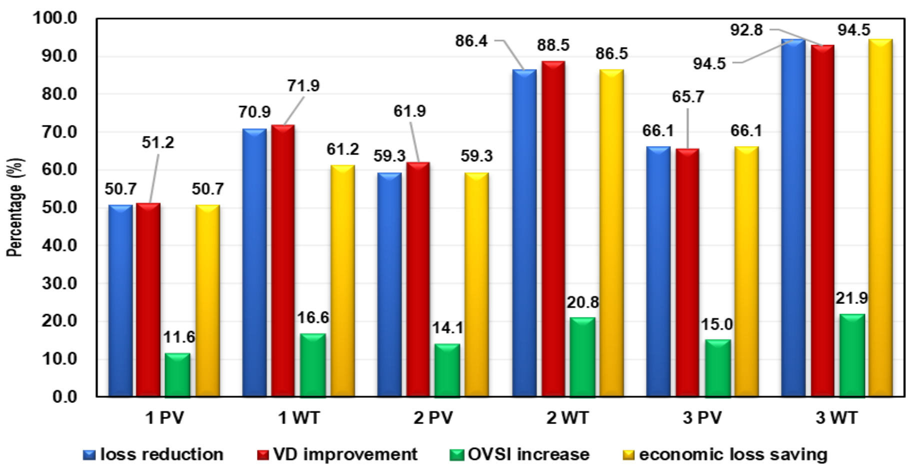

FIGURE 8. Effect of various penetration levels and type of RE-DG(s) on the techno-economic performance of 33 bus RDS.

$ compared to 98519.340 $ for the base case without any RESs.

The same trend in loss reduction and voltage support is observed when one WT is installed at bus 61 with an optimal size of 2243.9 kVA and a power factor of 0.8149. The HHO-PSO results reveal that the branch active power loss has reduced meaningfully in branch number 5, 6, and 52 to 60 (see Fig. 11); thus, the network losses are significantly minimized to 23.171 kW. Also, the minimum voltage of buses has maximized up to 0.9725 p.u along with OVSI of 65.705. Besides, the cost of losses is reduced, hence the amount of net annual saving enhanced to 88364.986 $.

In the second scenario, optimal planning of RE-DG units is examined considering multiple RE-DGs integration. In the case of two PV units, the bus numbers 17 and 61 are nominated as the best locations, and the optimal capacities of PV units are 531.5 kW and 1781.5 kW, respectively. It is observed that the contribution of two PVs successfully shares to reduce the active power losses to up to 71.677 kW, increase the minimum voltage point to 0.9789 p.u. and OVSI to 66.020. Moreover, the yearly economic loss considering two PVs is reduced to 31399.800 $. By the same way, the system losses and voltage profile are improved, together with increasing the annual saving when two WTs are optimally allocated at the same bus numbers, but with different capacities of 631.5 kVA/0.8137 PF at bus 17 and 2130.7 kW/0.8139 PF at bus 61.

On the other side, When the number of installed RE-DGs are increased to three, more refinement in the techno-economic performance of the distribution system are gained (see Fig. 12), in which the active power losses and annual economic loss are reduced to 69.449 kW and 30419.871 $ with 3 PVs and 4.27 kW and 1875.930 $ for the case of 3 WTs (see the cropped results summarized in Table 4). Moreover, the voltage profile of system buses has remarkably enhanced with a smooth uniform pattern as plotted in Fig. 9, which is confirmed by the betterment in the minimum value of

TABLE 4. Results of HHO-PSO for optimal allocation of RE-DG unit(s) (69 bus RDS).

Item	Single RE-DG		Multiple RE-DGs			
	PV	WT	2 PV	2 WT	3 PV	3 WT
P_{loss} (kW)	83.224	23.171	71.677	7.205	69.449	4.27
V_{min},bus (p.u.)	0.9683,27	0.9725,27	0.9789,65	0.9943,50,69	0.9786,65	0.9944,50
V_{max},bus (p.u.)	1.0,2	1.0,2&3	1.0,2	1.0,2&3	1.0,2&3	1.0,2,3&4
RES size and location	1872.7/1,61	2243.9/0.8149,61	531.5/1,17 1781.5/1,61	631.5/0.8137,17 2130.7/0.8139,61	571.7/1,11 1701.8/1,18 366.9/1,61	607.9/0.8314,11 457.6/0.8229,18 2055.7/0.8128,61
OVSI	64.611	65.705	66.020	67.469	66.216	67.727
VD_T (p.u)	0.872	0.587	0.5000	0.129	0.451	0.064
$AEL_{T,DG}$ *($)*	36457.674	10154.354	31396.050	3157.333	30419.871	1875.930
TAES ($)	62061.856	88365.176	67123.48	95362.197	68099.469	96643.410
CPU time (s)	7.403276	7.188476	7.463677	7.424984	8.038148	7.632566

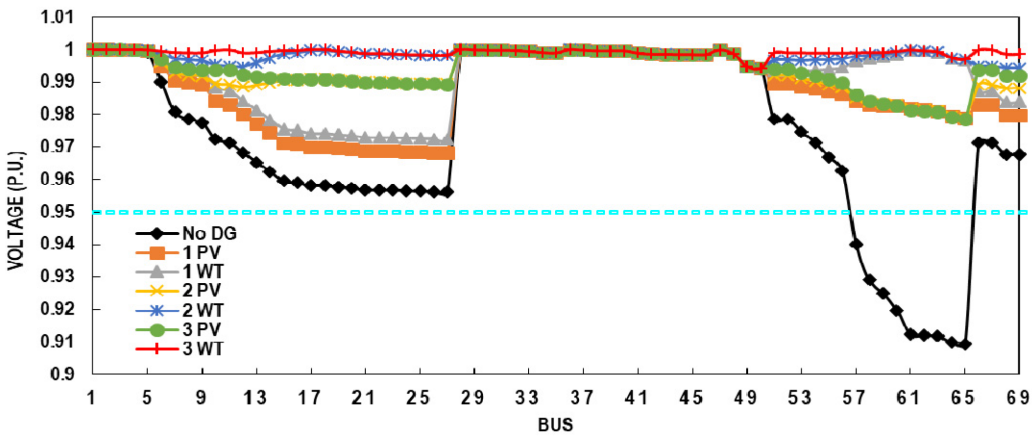

FIGURE 9. Voltage profile of 69 bus RDS without and with RE-DG unit(s).

buses voltages before and after connecting of RE-DGs. Also, the branch power active power losses in branch number 5, 6, and 52 to 60 are reduced to minimum values especially with inclusion of WTs as in Fig.11. Obviously, the results also show that WT with its ability of reactive power support has a better effect on the characteristics of the power network than PV.

Compared with literature, the proposed HHO-PSO algorithm provides better results, as displayed in Table 8. The best value of power losses (for instant, 83.224 kW with one PV and 23.171 kW with one WT) obtained by the proposed algorithm is less than the best values outlined in the previous works. This reveals the efficiency of the developed algorithm over the other methods to solve the problem of optimal allocation of RE-DG units in distribution networks.

D. CASE STUDY-3: PRACTICAL PORTUGUESE 94 BUS RDS

The proposed algorithm is implemented on a large-scale practical distribution system of 94-bus located in Portuguese. This power distribution network has some demanding particularities which impose heavier operating conditions to the system: due heavily loading and long distance the voltage profile is not within the acceptable voltage range.

After applying the proposed HHO-PSO algorithm, the impact of optimal planning and integration of RE-DGs is investigated and compared with literature. The obtained results by proposed methodology are summarized in Table 5, where the equality and inequality constraints are verified and founded within standard limits in the studied case. Also, the resultant network voltage and VSI profiles are shown in Fig. 13 and Fig. 14, while the graphical representation in Fig. 15 shows the branch power loss variation when PV unit with capacity of 2636 KW and single WT with capacity of 2968 kVA and power factor equals 0.89 is optimally engaged to the Portuguese 94-bus RDS at bus 19.

The obtained numerical results clearly indicate the positive implications of optimal planning and integration of RE-DG unit. The active power losses significantly reduced (from 362.86 kW to 132.39 kW with PV and 81.23 with WT), also a sustainable increase in the system voltage profile (0.93 p.u. and 0.95 in the cases of PV and WT, respectively) and enhancing the system stability indices (as revealed in Figs. 14, 15 and 16). Meanwhile, a subsequent significant

TABLE 5. Results of HHO-PSO for optimal allocation of RE-DG units (94 bus Portuguese RDS).

Item	Single RE-DG	
	PV	WT
P_{loss} (kW)	132.395	81.269
V_{min},bus (p.u.)	0.930,65	0.952,65
V_{max},bus (p.u.)	0.997,2	0.998,2
RES size and location	2636.0/1,19	2968.3/0.8936,19
OVSI	76.384	86.372
VD_T (p.u)	4.491	1.712
$AEL_{T,DG}$ ($)	57996.939	35603.7861
TAES ($)	34412.301	56805.479
CPU time (s)	7.403276	7.188476

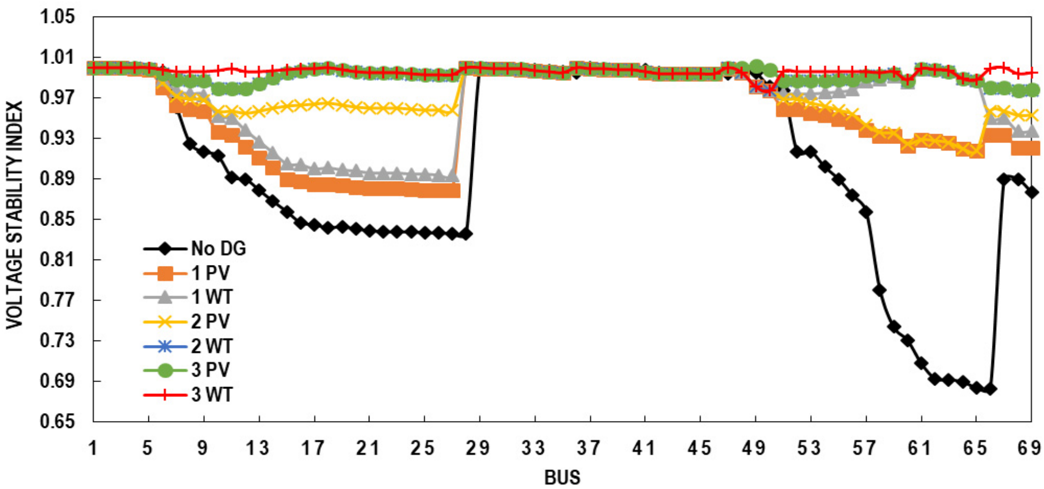

FIGURE 10. VSI profile of 69 bus RDS without and with RE-DG unit(s).

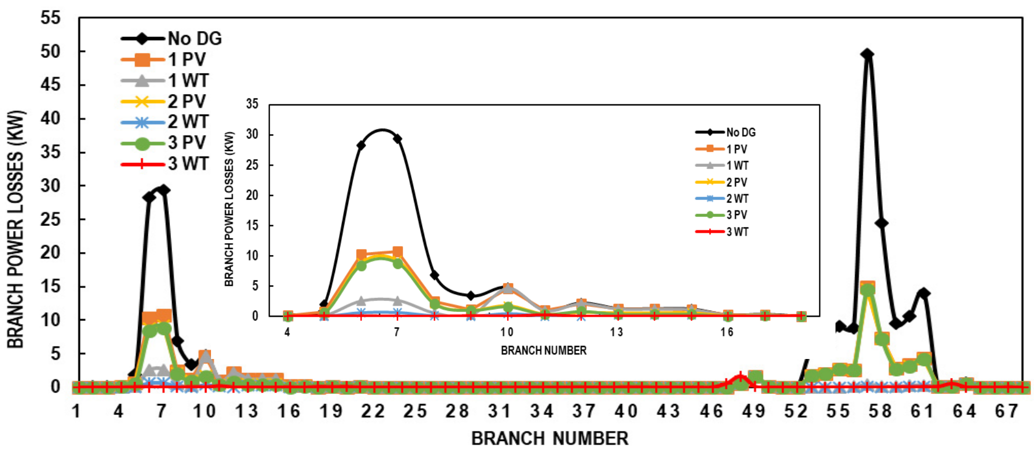

FIGURE 11. Branch active power loss profile of 69 bus RDS without and with RE-DG unit(s).

saving in the yearly economic loss is observed, where the total annual economic loss is reduced from 158932.68 $ to only 57996.939 $ with PV and 56805.479 with WT.

The comparative study with BSOA method [24], KHA and SKHA [31] confirms the advantageous and good computation efficacy of the proposed HHO-PSO method over BSOA in terms of solution quality as mentioned in Table 9.

E. PERFORMANCE EVALUATION OF THE PROPOSED HHO-PSO ALGORITHM

In general, the meta-heuristic algorithms are characterized by its randomness. Therefore, many trials have been made to prove the robustness of the HHO-PSO with 50 independent runs. Samples of the optimization objective convergences convergence curves of the three algorithms (i.e.,

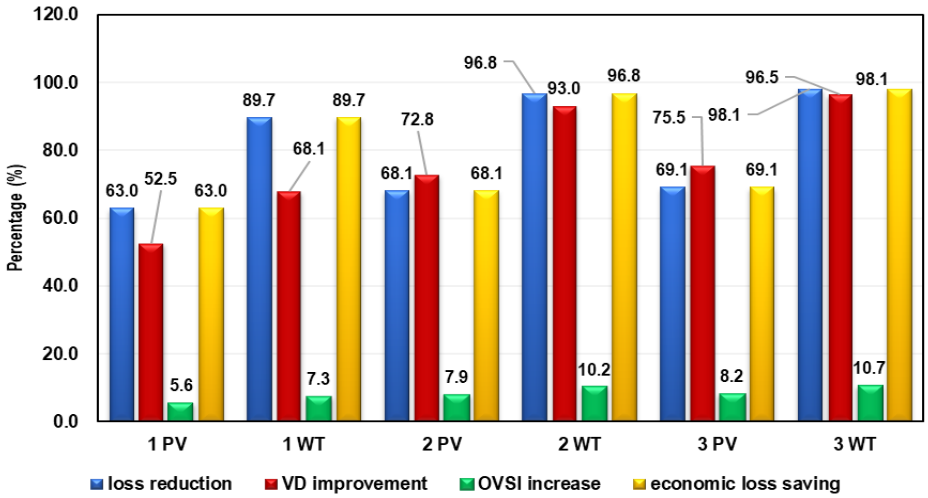

FIGURE 12. Effect of various penetration levels and type of RE-DG(s) on the techno-economic performance of 69 bus RDS.

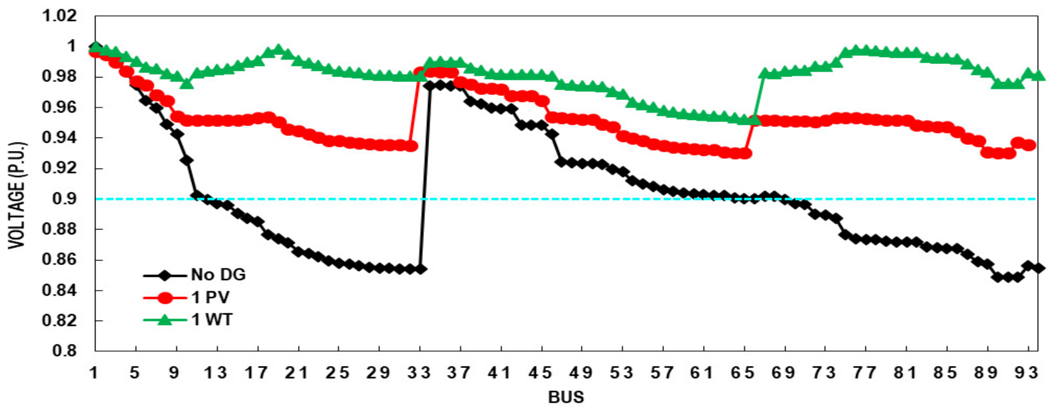

FIGURE 13. Voltage profile of 94 bus Portuguese RDS without and with RE-DG.

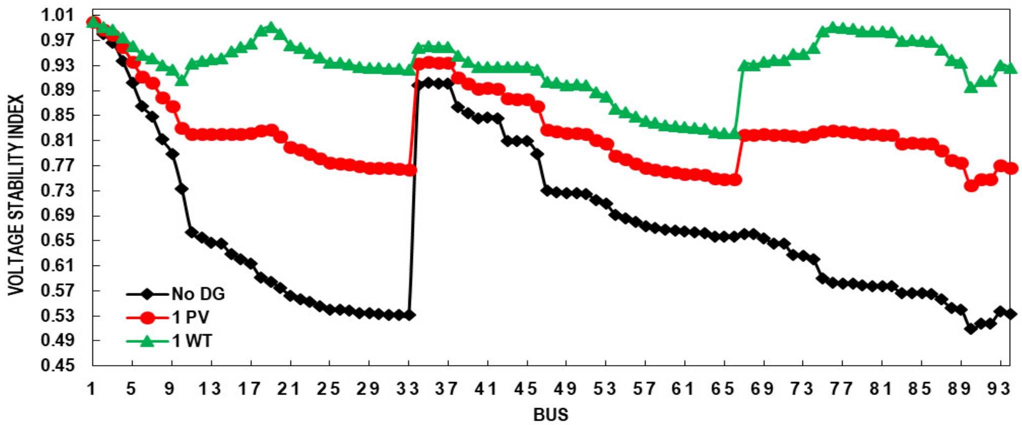

FIGURE 14. Bus VSI profile of 94 bus Portuguese RDS without and with RE-DG.

HHO-PSO, PSO, and HHO) of the *Ploss* are given in Fig. 16. and Fig. 17 In comparsion with HHO and PSO alogirhms, the results show that the HHO-PSO accelerates to the near-optimal solution smoothly, quickly, and in steady convergence characteristics.

Also, the robustness and efficacy of the proposed HHO-PSO over PSO and HHO algorithms are verified based on statistical factors, where many trials have been made. The minimum; maximum; mean; and the standard deviation (SD) of the objective function after 50 runs for IEEE 33-bus system

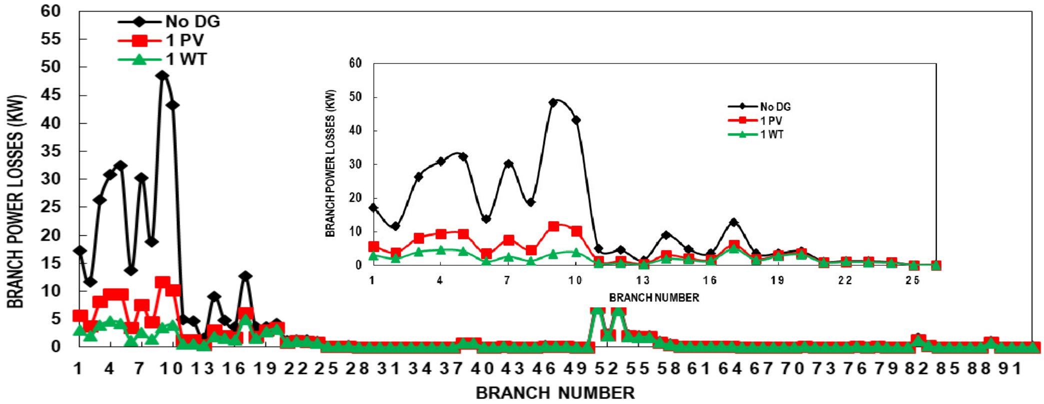

FIGURE 15. Brach active power loss profile of 94 bus RDS without and with RES-DG.

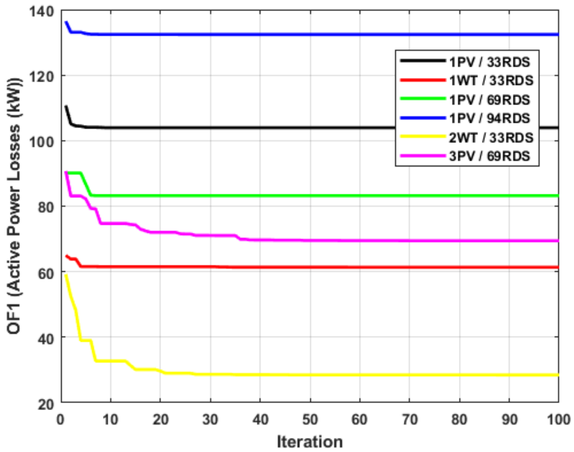

FIGURE 16. Convergence rate of HHO-PSO algorithm for optimal allocation of RE-DG units (sample cases).

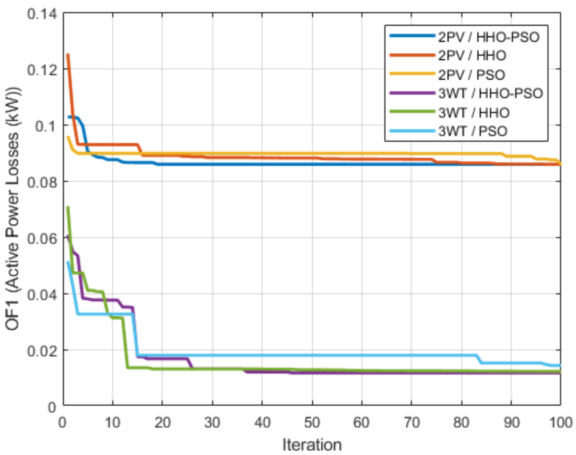

FIGURE 17. Comparsion of the convergences characteristics of HHO-PSO *vs* HHO and PSO (*Ploss* objective, CASE STUDY-1).

with scenarios of two PVs and three WTs as presented in Table 6. It can be seen that the proposed HHO-PSO algorithm has more stronger statistical indicators than the other

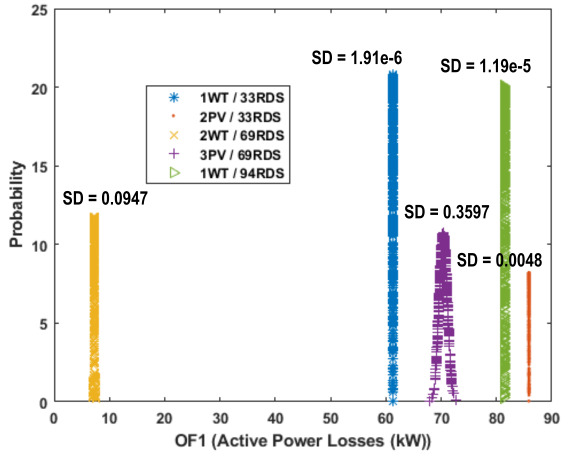

FIGURE 18. PDFs for active power losses (sample cases).

TABLE 6. Comparison of statistical indicators of HHO-PSO *vs* HHO and PSO (CASE STUDY-1).

Algorithm	Min	Max	Mean	SD
		2 PV units		
PSO	85.87	86.85	85.98	0.16707
HHO	85.87	86.20	85.90	0.04781
HHO-PSO	85.87	85.93	85.88	0.00482
		3 WT units		
PSO	14.30	36.91	22.16	4.99569
HHO	12.19	24.93	20.11	0.95293
HHO-PSO	11.66	20.58	13.89	0.79082

algorithms. Similar indicators can be extended straightforwardly to other cases as well.

Furthermore, due to the stochastic and intermittent nature of the WT and PV generation, the RE-DG unit planning results need to be considered as random variables. So, Monte Carlo simulation (MCS) is used to appraise the statistical features of obtained results. Fig. 18 shows a sample of PDFs for the acti ve power losses (i.e., *OF1)* got with 500 samples in test cases of single and multiple allocations of RE-DGs with thee studied RDSs. From the results obtained by Fig. 18, the best solution obtained in each case is always very close

TABLE 7. Comparison of HHO-PSO results for 33 bus RDS.

Ref	Methods	1 PV unit			2 PV units			3 PV units			1 WT unit			2 WT units			3 WT units		
		RE-DG data (kVA/PF,Bus)	*P_{loss} (kW)*	*V_{min} (p.u)*	*RE-DG data (kVA/PF,Bus)*	*P_{loss} (kW)*	*V_{min} (p.u)*	*RE-DG data (kVA/PF,Bus)*	*P_{loss} (kW)*	*V_{min} (p.u)*	*RE-DG data (kVA/PF,Bus)*	*P_{loss} (kW)*	*V_{min} (p.u)*	*RE-DG data (kVA/PF,Bus)*	*P_{loss} (kW)*	*V_{min} (p.u)*	*RE-DG data (kVA/PF,Bus)*	*P_{loss} (kW)*	*V_{min} (p.u)*
[24]	BSOA	1857.5/1,8	118.12	0.9441	880/1,13 924/1,31	89.34	0.9665	632/1,13 487/1,28 550/1,31	89.05	0.9554	2265.24/0.82	82.78	0.9549	777/0.89,13 1032/0.7,29	31.98	0.9796	1059/0.85,6 1059/0.85,30 741/0.85,14	23.05	
[25]	MOCD	2581.87/1,6	110.851	0.9423	NR	NR	NR	801.84/1,13 1091.46/1,24 1046.58/1,30	72.848	0.9686	NR	NR	NR	NR	NR	NR	NR	NR	NR
[26]	WOA	1542.67/1,30	125.161	0.9272	NR	NR	NR	NR	NR	NR	1940.33/0.9,30	78.4337	0.9386	NR	NR	NR	NR	NR	NR
[27]	ABC	2400/1,6	109.3		NR	NR	NR	NR	NR	NR				NR	NR	NR	NR	NR	NR
[28]	BSA	1857/1,8	118.12	0.9441	782/1,13 1708/1,30	93.67	0.9638	NR	NR	NR	2.653/0.714,6	74.68	0.9498	870.87/0.90,13 1936.5/0.83,30	30.85	0.9216	NR	NR	NR
[29]	PSO	2590/1,6	111.10	0.9424	1000/1,12 1020/1,30	87.5	0.9650	880/1,13 1090/1,24 1010/1,30	73.20	0.9684	3096/0.826,6	67.857	0.9598	994.73/0.822,12 2074.87/0.82,29	39.10	0.9828	932.70/0.82,13 1231.42/0.87,24 1228.71/0.83,30	15	0.9892
[29]	Analytical	2600/1,6	111.10	0.9425	1800/1,6 720/1,14	91.36	0.9539	900/1,13 900/1,24 900/1,30	81.05	------	3102/0.85,6	68.157	0.9575	2117.36/0.85,6 1058.42/0.85,30	44.84	0.9600	1094.08/0.85,6 740.95/0.85,14 1058.42/0.85,30	23.05	0.9821
[30]	IWD	2490/1,6	111.01		NR	*NR*	NR	600.3/1,9 300/1,16 1011.2/1,30	85.78	600.3/1,9 300/1,16 1011.2/1,30	NR	NR	NR	NR	NR	NR	NR	NR	NR
[31]	SKHA	2590.21/1,6	111.0188	0.9424	13/851.6 30/1157.6	87.1656	0.9685	1053.63/1,30 1091.38/1,24 801.81/1,13	72.7853	0.9687	NR	NR	NR	NR	NR	NR	NR	NR	NR
[32]	DA	2590.2/1,6	111.0338	NR	NR	NR	NR	NR	NR	NR	3073.5/0.9,6	70.8652	0.9566	NR	NR	NR	NR	NR	NR
[33]	MOEA/D	2575/1,6	103.95	0.9454	844 (13), 1156 (30)	103.95	0.9684	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[34]	FA	1190.4/1,60	116.7		1013.1/1,30 612.8/1,14	96.9	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[35]	GWO	2590/1,6	111.018	0.9455	852/1,13 1158,1/30	87.164	0.9714	802/1,13 1090/1,24 1054/1,30	72.748	0.97148	3106/0.82,6	67.855	0.9584	932/0.9,13 1558/0.72,30	28.50	0.9802	878.902/0.9,13 1182/0.9,24 1454/0.71,30	11.74	0.9922
[36]	Analytical	NR	NR	NR	NR	NR	NR	1112.4/1,16 487.4/1,18 867.9/1,30	82.03	0.9676	NR	NR	NR	NR	NR	NR	1382.9/0.866,6 551.7/0.866,14 1062.5/0.866,30	26.72	0.9826
[37]	GA-PSO	NR	NR	NR	NR	NR	NR	925/1,11 836/1,16 1200/1,32	103.4	0.98083	NR	NR	NR	NR	NR	NR	NR	NR	NR
[37]	GA	NR	NR	NR	NR	NR	NR	1500/1,11 422.8/1,29 1071.4/1,30	106.300	0.98094	NR	NR	NR	NR	NR	NR	NR	NR	NR
[38]	QOTLBO	NR	NR	NR	NR	NR	NR	1083.4/1,13 1187.6/1,26 1199.2/1,30	103.409		NR	NR	NR	NR	NR	NR	NR	NR	NR
[39]	MOIDSA	NR	NR	NR	NR	NR	NR	968.7/1,30 800/1,13 1036.3/1,25	75.02	0.9657	NR	NR	NR	NR	NR	NR	374.6/0.866,32 713/0.866,14 1028.7/0.866,30	19.29	0.9881
[42]	PSO	3150/1,6	115.29	NR	NR	NR	NR	NR	NR	NR	3020/0.85,6	67.95	-	NR	NR	NR	NR	NR	NR
[45]	BFOA	NR	NR	NR	NR	NR	NR	621.1/1,14 198.4/1,18 1067.2/1,32	89.9	0.9075	NR	NR	NR	NR	NR	NR	784.98/0.866,14 150.38/0.866,15 1280.02/0.866,32	37.85	0.9802
[46]	KHA	NR	NR	NR	NR	NR	NR	810.7/1,6 836.8/1,18 841.0/1,30	75.412	0.9610	NR	NR	NR	NR	NR	NR	984.9/0.866,13 1039.2/0.866,24 1039.1/0.866,30	19.578	0.9816
[58]	Analytical	2490/1,6	111.24	NR				NR	NR	NR				NR	NR	NR	NR	NR	
[59]	DAPSO	1212/1,8	127.17	0.9349	NR	NR	NR	681/1,10 600/1,18 719/1,31	92.55	0.9654				NR	NR	NR	NR	NR	NR
[60]	Analytical	2601/1,6	111.1	NR	NR	NR	NR	720/1,18 810/1,33 900/1,25	85.07		3103/0.85,6	68.2	-	NR	NR	NR	NR	NR	NR
[61]	Analytical	2494/1,6	111.146	0.9412	NR	NR	NR	NR	NR	NR	3011.3/0.9,6	70.6072	0.9566	NR	NR	NR	NR	NR	NR
[62]	Hybrid	2490/1,6	111.170	NR	830/1,13 1110/1,13	87.28	NR	790/1,13 1070/1,24 1010/1,30	72.890	NR	3028/0.82,6	67.937	NR	1039/0.91.13 1508/0.72.30	28.98	NR	873/0.9,13 1186/0.89,24 1439/0.71,30	11.76	NR
[63]	HAS/PABC	2598/1,6	111.03	0.9425	NR	NR	NR	NR	NR	NR	3011.76/0.85,6	68.29	0.9568	NR	NR	NR	1014/0.85, 12 1363.5/0.85,30 960/0.85,25	15.91	0.9889
Current study	**Proposed HHO-PSO**	**2574.3/1,6**	**103.944**	**0.9510**	**846.0/1,13 1158.2/1,30**	**85.870**	**0.968**	**761.4/1,14 1094.7 /1,24 1068.4/1,30**	**71.437**	**0.9687**	**3088.0/0.8239,6**	**61.359**	**0.967**	**1064.9/0.9042,12 1504.6/0.7228,30**	**28.579**	**0.9803**	**484.5/0.,12 1143.8 /0.8961,24 1484.4/0.7069,30**	**11.659**	**0.9930**

to the mean value with very small value of SD– Similar results can be extracted straightforwardly to the other cases as well.

VI. CONCLUSION

In this paper, the optimal planning and impacts of RE-based DG units particularly WT and PV have been addressed for techno-economic benefits maximization of ADSs. A novel HHO-PSO algorithm has presented for the optimal allocation and sizing of RE-DG units in the distribution system. The stochastic nature of solar and wind resources is correctly modeled using Beta and Weibull PDFs, repetitively. The proposed methodology has been successfully implemented on two standard systems; IEEE 33 bus and 69 bus RDSs, and practical Portuguese 94 bus RDS as well. Various scenarios with different penetration levels of PV and WT units are examined.

The obtained simulation results could lead to conclusions highlighted as follows:

- The HHO-PSO algrothim enables robust and powerful tool for optimal planning of RE-DG units compared to HHO and PSO.
- The proper modeling of the uncertainties of solar and wind power results in a more realistic and efficient investigation of the impacts of RE-DGs on the techno-economic performance of ADSs.
- Considering PV and WT power generators, the obtained results signify the effectiveness of the proposed algorithm through a brilliant reduction in active power losses and a considerable saving in annual economic loss, in addition to high-quality electric service by flat voltage profile and a more stable system.
- The more increase in the penetration level of RE-DGs, the more melioration in operational and financial indices of the distribution system, especially with the case of WTs.
- In comparison with the well-known stohastic and analystical techniques reported in the literature, the proposed HHO-PSO approach is of best results and applicability for efficient integration of renewable enenrgy sources with better convergence speed and computational efficacy.

For future research directions, further investigation of the impacts of simultaneous installation of PV and WT into distribution systems with including energy storage systems can be also conducted. Meanwhile, the future efforts can be dedicated to consider the time variation and uncertainties in load demands. This projected to promote precision of the practical significance of ADS planning.

TABLE 8. Comparison of HHO-PSO results for 69 bus RDS.

Ref	Method	1 PV unit			2 PV units			3 PV units			1 WT unit			2 WT units			3 WT units		
		RE-DG data (kVA/PF,Bus)	P_{loss} *(kW)*	V_{min} *(p.u)*	*RE-DG data (kVA/PF,Bus)*	P_{loss} *(kW)*	V_{min} *(p.u)*	*RE-DG data (kVA/PF,Bus)*	P_{loss} *(kW)*	V_{min} *(p.u)*	*RE-DG data (kVA/PF,Bus)*	P_{loss} *(kW)*	V_{min} *(p.u)*	*RE-DG data (kVA/PF,Bus)*	P_{loss} *(kW)*	V_{min} *(p.u)*	*RE-DG data (kVA/PF,Bus)*	P_{loss} *(kW)*	V_{min} *(p.u)*
[24]	BSOA	NR	NR	NR	NR	NR	NR	500/1,9 521/1,33 1929/1,61	83.68	0.9716	NR	NR	NR	NR	NR	NR	NR	NR	NR
[25]	MOCD	NR	NR	NR	530.99/1,17 1781.3/1,61	71.67	NR	525.93/1,11 380.18/1,18 1718.96/1,61	94.436	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[26]	WOA	1872.82/1,61	83.2279	0.9683	NR	NR	NR	NR	NR	NR	2217.39/0.9,61	27.9646	0.9724	NR	NR	NR	NR	NR	NR
[27]	ABC	1900/1,61	83.31		NR	NR	NR	NR	NR	NR				NR	NR	NR	NR	NR	NR
[29]	PSO	1810/1,61	80.78	NR	1810/1,61 510/1,17	68.85	0.9806	1810/1,61 510/1,17 720/1,50	67.30	NR	2207/0.824,61	23.21	NR	642.04/0.816,17 2107.11/0.827,61	7.45	0.9943	613.35/0.828,18 845.05/0.828,50 2086.03/0.832,61	5.08	NR
[29]	Analytical	1900/1,61	83.43	NR	1700/1,61 510/1,17	72.12	0.9765	1700/1,61 510/1,17 340/1,11	70.14	NR	2243/0.82,61	23.21	NR	658.58/0.82,17 2194.24/0.82,61	7.45	0.9944	1094.08/0.82,61 740.95/0.82,17 1058.42/0.82,50	5.08	NR
[30]	IWD	NR	NR	NR	NR	NR	NR	2999/1,17 1320/1,60 438.8/1,63	73.55	2999/1,17 1320/1,60 438.8/1,63	NR	NR	NR	NR	NR	NR	NR	NR	NR
[32]	DA	1872.7/1,61	83.22	0.9685	NR	NR	NR	NR	NR	NR	2217/0.9,61	27.9636	0.9728	NR	NR	NR	NR	NR	NR
[35]	GWO	1872/1,61	83.222	0.9682	531/1,17 1781/1,61	71.943	0.9799	527/1,13 380/1,17 1718/1,61	94.425	0.9799	2246/0.81,61	23.16	0.9724	68/0.82,17 2127/0.81,61	7.20	0.9941	614/0.81,11 452/0.83,18 2056/0.81,61	4.26	0.9942
[36]	Analytical	NR	NR	NR	NR	NR	NR	420.4/1,18 1331.1/1,60 429.8/1,65	71.1	0.98115	NR	NR	NR	NR	NR	NR	549.8/0.866,18 1195.4/0.866,60 312.2/0.866,65	16.26	0.9885
[37]	GA-PSO	NR	NR	NR	NR	NR	NR	884.9/1,63 1196/1,61 910.5/1,21	81.1	0.99249	NR	NR	NR	NR	NR	NR	NR	NR	NR
[37]	GA	NR	NR	NR	NR	NR	NR	9297/1,21 1331.1,60 429.8,65	89	0.99360	NR	NR	NR	NR	NR	NR	NR	NR	NR
[38]	QOTLBO	NR	NR	NR	NR	NR	NR	811.4/1,15 1147.0/1,61 1002.2,63	80.585	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[39]	MOIDSA	NR	NR	NR	NR	NR	NR	492.986/1,11 378.385/1,18 1672.528/1,61	66.977	NR	NR	NR	NR	NR	NR	NR	392.4/0.866,18 1794.4/0.866,61 1170.0/0.866,11	5.9021	NR
[40]	CSA	2000/1,61	83.8		600/1,22 2100/1,61	76.4	NR	NR	NR	NR	2300/NR,61	52.6		800/NR,18 2000/NR,61	39.9				NR
[41]	PSO	1866.2/1,61	83.2	0.9684	NR	NR	NR	NR	NR	NR	2210/0.836,61	23.4	0.9722	NR	NR	NR	NR	NR	NR
[40]	SGA	2300/1,61	89.4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[40]	PSO	2000/1,61	83.8	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[42]	PSO	1807.8/1,61	83.37		NR	NR	NR	NR	NR	NR	2243/0.82,61	23.18		NR	NR	NR	NR	NR	NR
[43]	MTLBO	1819.941/1,61	83.323		519.705/1,17 1732.004/1,61	71.776	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[44]	BB-BC	1872.5,61	83.2246	NR	NR	NR	NR	NR	NR	NR	2223/0.81,61	23.1737	NR	NR	NR	NR	NR	NR	NR
[45]	BFOA	NR	NR	NR	NR	NR	NR	27/295.4/1,27 446/1,65 1345.1/1,61	75.23	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[46]	KHA	NR	NR	NR	NR	NR	NR	496.2/1,12 311.3/1,22 1735.4/1,61	94.563	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[64]	Analytical	1807.8/1,61	92	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
[60]	Analytical	NR	NR	NR	NR	NR	NR	NR	NR	NR	2243/0.82,61	22.62		2195/0.82,61 659/0.82,17	7.25		2073/0.82,61 622/0.82,17 829/0.82,50	4.95	NR
[61]	Analytical	1832.54/1,61	83.1951	0.9685	NR	NR	NR	NR	NR	NR	2236.704/0.9,61	27.37953	0.97284	NR	NR	NR	NR	NR	NR
[62]	Hybrid	1810/1,61	83.372	NR	520/1,17 1720/1,60	71.82	NR	510/1,11 380/1,17 1670/1,61	94.52	NR	2200/0.82,61	23.92	NR	630/0.82,17 2120/0.81,61	7.20	??	480/0.77,18 2060/0.83,61 530/0.82,66	4.3	NR
Current study	**Proposed HHO-PSO**	**1872.7/1,61**	**83.224**	**0.968**	**531.5/1,17 1781.5/1,61**	**71.677**	**0.979**	**571.7/1,11 1701.8/1,18 366.9/1,61**	**69.449**	**0.979**	**2243.9/0.8149,61**	**23.171**	**0.972**	**631.5/0.8137,17 2130.7/0.8139,61**	**7.205**	**0.994**	**607.9/0.8314,11 457.6/0.8229,18 2055.7/0.8128,61**	**4.27**	**0.994**

TABLE 9. Comparison of HHO-PSO results for practical portuguese 94 bus RDS.

Item	1 PV				1 WT	
	BSOA [24]	**KHA** [31]	**SKHA** [31]	**HHO-PSO**	**BSOA** [24]	**HHO-PSO**
P_{loss} *(kW)*	153.56	132.3957	132.3957	132.3240	85.13 (76.54% reduction)	81.27
%loss reduction	54.60	63.5131	63.5131	63.5330	76.5391	77.6029
V_{min} *(p.u.),bus*	0.9276	0.9301	0.9301	0.9306	0.9519	0.9526
V_{max}*(p.u.),bus*	0.9967	0.9968	0.9968	0.9972	0.9980	0.9982
RE-DG data (kVA/PF,Bus)	2398.5/1,21	2636.0175/1,19	2636.018/1,19	2636/1,19	2398.5/0.532,18	2968.3/0.894,19
CPU time (s)	118	22.57	21.17	7.403276	234	7.188476

APPENDIX A

See Table 7.

APPENDIX B

See Table 8.

APPENDIX C

See Table 9.

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