Multi-Objective Optimal Design of Solar and Wind Hybrid Renewable Energy Systems Considering Daily Uncertainties

Nasreddine Belbachir[1], and Mohamed Zellagui[2]

[1]Department of Electrical Engineering, University of Mostaganem, Mostaganem, Algeria
[2]Department of Electrical Engineering, University of Batna 2, Batna, Algeria

[*]Corresponding author; E-mail: nasreddine.belbachir.etu@univ-mosta.dz

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ABSTRACT

The problem of energy supply kept floating on the surface. Hybrid Renewable Energy Systems (HRES) are one of the solutions and references to configure the power system and generation. The optimal sizing and placement of HRES in the Electrical Distribution Systems (EDS) is a trendy problem that may be solved using different approaches and algorithms due to their high complexity. The HRES presence in the EDS is so beneficial and advantageous, where in general lead to, power losses reduction, voltage profiles enhancement, growth of the system reliability and loadability, also the improvement of the system's protection and security. Those benefits are reachable unless the RES is properly optimized in location and size based on different objective functions. In this context, this paper is devoted to utilizing a recent nature-inspired metaheuristic approach called Ant Lion Optimizer (ALO) algorithm to optimally integrate HRES units based on photovoltaic (PV) and wind turbine (WT) sources into the EDS when optimizing and minimizing a multi-objective function (MOF) represented as the total of the techno-economic parameters are the total power losses (TAPL), the total voltage deviation (TVD), the total operating time of overcurrent relays (TOT), and the investments cost of both PV and WT power sources (ICPV) and (ICWT), considering the daily uncertainties of their generation and the load demand. The ALO is validated on the test system of IEEE 33-bus.

Nomenclature

RES	Renewable Energy System	T_i	Relay's operating time
R_{ij}	Resistance of the line	TDS	Time dial setting
N_{bus}	Bus number	A and B	Relays' constants set to 0.14, 0.02
P_i, P_j	Active powers	M	Multiple of pickup current
Q_i, Q_j	Reactive powers	I_F, I_P	Fault and pickup current
δ_i, δ_j	Angles at positions i and j	N_{Relay}	Relays' number
V_i, V_j	Voltages at positions i and j	N_{PV} and N_{WT}	Number of PV and WT units
Q_G, P_G	Total reactive and active powers	C_{PV} and C_{WT}	Cost of one PV and one WT in \$/kW
P_{RES}, Q_{RES}	Total powers from RES	P_{PV} and P_{WT}	Active power by PV and WT in kW
P_{Load}, Q_{Load}	Total active and reactive load	$C_{Capital}$	Capital cost
V_{min}, V_{max}	Specified voltage limits	$C_{O\&M}$	Operation and maintenance cost
ΔV	Drops of the line's voltage	$RES_{Position}$	Position of RES units
S_{ij}, S_{max}	Apparent and maximum power	$N_{RES.max}$	Maximum number of RES units
$n_{RES,\,i}$	Location of RES units at bus i	K_v, K_i	Current and coefficients of voltage
λ	Parameter of load demand	N_{OT}	Cell's operating temperature

Q_k and P_k	Powers generated at bus k	FF	Fill factor
Q_{ok} and P_{ok}	Load powers at bus k	V_{oc}	Open-circuit voltage
PDF	Probability Density Function	I_{sc}	Current of short-circuit
N	Modules' number	V_{MPP}, I_{MPP}	Maximum voltage and current
μ, σ	Mean and standard deviation	s	Solar irradiance's random variable
v	Average wind speed	f_b (s)	Beta's distribution function
v_{ci}, v_{ci}, v_{co}	Cut-in, rated, and cut-off speed	s_1, s_2	Solar irradiance limits of state s

I. Introduction

I.1. Problem Statement

The electricity tendrils go deep into every industry that is necessary for society's survival. As a result, adequate and dependable access to electricity is critical to the survival of contemporary civilization [1]. Renewable energy systems are becoming more cost-effective, and they now account for a significant portion of the global power plant mix [2].

Hybrid Renewable Energy Systems (HRES) have greatly aided the increase of renewable energy penetration in the worldwide power plant mix in recent years [3, 4]. The configuration HRESs with solar and wind energy has been the preferred choice in such applications due to their complementing qualities, established technology, and availability in most places [5].

These advantages are contingent on the features of Distributed Generators (DG) units such as photovoltaic panels, wind turbines, and reciprocating engines, as well as the characteristics of the loads, local renewable resources, and electrical distribution systems layout [6].

Incorporating HRESs into distribution systems now has both technical and economic implications. Photovoltaic and wind energy based HRES are widely utilized and have a long lifespan [7]. A critical part of HRES operations is the energy management system. When it comes to the necessity of correct HRES size during the pre-installation stage, finding the best allocation (location and setting) for HRES is imperative [8].

I.2. Literature Review

Different optimization algorithms and approaches are developed by the research community and has been discussed in several studies from different perspectives: applied Particle Swarm Optimization (PSO) algorithm to minimize the total cost, gas emission, and maximum reliability [9], and PSO algorithm for the minimization of the total annual cost with incorporating the load uncertainty [10]. Used the Ant Colony Optimization (ACO) algorithm for minimizing the capital and maintenance cost of hybrid system [11], Cuckoo Search algorithm (CSA) for minimizing total system cost [12], new Adaptive Genetic Algorithm with Cauchy mutation (AGA) to minimize the total investment cost of PV and WT units [13], Non-Dominated-Sorting Genetic Algorithm (NSGA) to minimize the social cost and the utility system cost [14]. Applied the Multi-Objective Water Cycle Algorithm (MOWCA) to reduce various techno-economic and environmental parameters in distribution system [15], and Modified Discrete Bat Algorithm (MDBAT) to reduce the total investment and maintenance cost [16].

In 2020, applied Moth–Flame Optimization (MFO) algorithm for minimizing the cost of energy not-supplied for customers [17], Manta Ray Foraging Optimization (MRFO) algorithm was applied for minimization of power losses and voltage deviation, with maximization of voltage stability index [18], Whale Optimization Algorithm (WOA) for several reliability indices [19], used Opposition based Social Spider Optimization (OSSO) to minimize the total cost of PV and WT units [20], Hybrid SA and PSO for loss sensitivity index [21] and applied various optimization algorithms to maximum allowable loss of power supply [22].

Recently, applied new Improved Crow Search Algorithm (ICSA) to reduce technical and economic parameters [23], Grey Wolf Optimizer (GWO) algorithm to minimize simultaneous technical indices considering the seasonal uncertainties [24], and used Equilibrium Optimizer (EO) algorithm to reach environmental and techno-economic benefits in electrical distribution systems [25].

Where, the Ant Lion Optimizer (ALO) algorithm was developed originally by Mirijalili in 2015, to emulate the behavior's hunting of ant lions in nature [26]. The ALO is a nature-inspired approach devoted to solve optimization problems when simulating the hunting steps of ant lions. The highlighted review presents the applications that used ALO algorithm to solve different problems of optimization [27]. It comprises various advantages: easy, scalable, flexible, and a huge balance between the exploration and exploitation [28].

I.3. Contribution of the Paper

This paper aim to solve the optimal allocation of HRESs problem in a distribution system using a new optimization algorithm to reduce various technical and economic parameters in standard IEEE 33-bus distribution system. The paper principal contributions can be summarized as follow:

- A new application of the ALO algorithm for minimizing the multi-objective functions with capturing the size of incorporating hybrid wind and photovoltaic systems under daily uncertainties.

- Proposed new multiple objective functions based on various technical and economic parameters.

- Validating the developed algorithm using IEEE 33-bus distribution systems with optimal integration HRESs.

- The simulation results demonstrate the suggested algorithm resilience of a significant reduction in power loss, improvement of voltage profile and protection system, also reaching a favorable investment cost of the HRESs.

This paper comprises five sections followed by a references list, which is organized as: Section 2 demonstrates the mathematical formulation of the problem. Section 3 presents the modeling of various uncertainties of load-source power variation of HRES. Section 4 contains the results of the simulation, discussions, and comparisons. Finally, the conclusions and future perspectives are addressed in Section 5.

II. Mathematical Problem Formulation

II.1. Multi-Objective Functions

The Multi-Objective Functions (MOF) that have been proposed in this paper, is devoted to searching the optimal placement and sizing of multiple HRESs based on multiple PV and WT units into the distribution system. The next equation represents its mathematical formulation:

$$MOF = Minimize \sum_{i=1}^{N_{Bus}} \sum_{j=2}^{N_{Bus}} \sum_{i=1}^{N_{Relay}} \sum_{j=1}^{N_{PV}} \sum_{j=1}^{N_{WT}} TAPL_{i,j} + TVD_j + TOT_i + IC_{PV,i} + IC_{WT,i} \tag{1}$$

The first technical parameter is the TAPL, which is formulated as follows [29]:

$$TAPL_{i,j} = \sum_{i=1}^{N_{Bus}} \sum_{j=2}^{N_{Bus}} APL_{i,j} \tag{2}$$

$$APL_{i,j} = \frac{R_{ij}}{V_i V_j} \cos(\delta_i - \delta_j)\left(P_i P_j + Q_i Q_j\right) + \frac{R_{ij}}{V_i V_j} \sin\left(\delta_i - \delta_j\right)\left(Q_i P_j + P_i Q_j\right) \tag{3}$$

The second technical parameter is the TVD, and it is formulated as [30, 31]:

$$TVD_j = \sum_{j=2}^{N_{Bus}} \left|1 - V_j\right| \tag{4}$$

The third technical parameter is the TOT of the overcurrent relays installed in distrinbution system [32, 33]:

$$TOT_i = \sum_{i=1}^{N_{Relay}} T_i \tag{5}$$

$$T_i = TDS_i\left(\frac{A}{M_i^B - 1}\right) \tag{6}$$

$$M_i = \frac{I_F}{I_P} \tag{7}$$

The fourth economical parameter represents the investment cost IC_{PV} of PV. The IC_{PV} as the total of installed PV units' capital cost, operation, and maintenance cost [34], could be formulated as:

$$IC_{PV} = \sum_{i=1}^{N_{PV}} C_{PV}.P_{PV,i} \tag{8}$$

$$C_{PV} = C_{Capital}^{PV}.C_{O\&M}^{PV} \quad (\$/\text{kW}) \tag{9}$$

The capital cost ($C^{PV}{}_{Capital}$) is 4000 $/kW, which comprises PV modules, inverter, and installation engineering. Also, the maintenance cost ($C^{PV}{}_{O\&M}$) is 20 $/kW.

The fifth economical parameter represents the investment cost IC_{WT} of WT. The IC_{WT} as the total of installed WT units' capital cost, operation, and maintenance cost [35], could be formulated as:

$$IC_{WT} = \sum_{i=1}^{N_{WT}} C_{WT}.P_{WT,i} \tag{10}$$

$$C_{WT} = C_{Capital}^{WT}.C_{O\&M}^{WT} \quad (\$/\text{kW}) \tag{11}$$

The capital cost ($C^{WT}{}_{Capital}$) is 5800 $/kW, which comprises wind turbine, inverter, transportationm and installation engineering. The maintenance cost ($C^{WT}{}_{O\&M}$) is 40 $/kW.

II.2. Equality Constraints

$$P_G + P_{RES} = P_{Load} + APL \tag{12}$$

$$Q_G + Q_{RES} = Q_{Load} + RPL \tag{13}$$

II.3. Dribution Line Inequality Constraints

$$V_{min} \le |V_i| \le V_{max} \tag{14}$$

$$|1 - V_j| \le \Delta V_{max} \tag{15}$$

$$|S_{ij}| \le S_{\max} \tag{16}$$

II.4. RES Units Inequality Constraints

$$P_{RES}^{min} \leq P_{RES} \leq P_{RES}^{max} \tag{18}$$

$$Q_{RES}^{min} \leq Q_{RES} \leq Q_{RES}^{max} \tag{19}$$

$$\sum_{i=1}^{N_{RES}} P_{RES}(i) \leq \sum_{i=1}^{N_{Bus}} P_D(i) \tag{20}$$

$$\sum_{i=1}^{N_{RES}} Q_{RES}(i) \leq \sum_{i=1}^{N_{Bus}} P_D(i) \tag{21}$$

$$2 \leq RES_{Position} \leq N_{Bus} \tag{22}$$

$$N_{RES} \leq N_{RES.max} \tag{23}$$

$$n_{RES,i}/Location \leq 1 \tag{24}$$

$$PF_{RES}^{min} \leq PF_{RES} \leq PF_{RES}^{max} \tag{25}$$

$$PF_{RES} = \frac{P_{RES}}{\sqrt{P_{RES}^2 + Q_{RES}^2}} \tag{26}$$

III. Modeling Daily Uncertainties

III.1. Load Demand Uncertainty

The next equations illustrate the load demand uncertainties modeling [36, 37]:

$$P_k(t) = \lambda(t) \times P_{ok} \tag{27}$$

$$Q_k(t) = \lambda(t) \times Q_{ok} \tag{28}$$

In figure 1, the curve demonstrates the daily load demand variation represented in 24 hours.

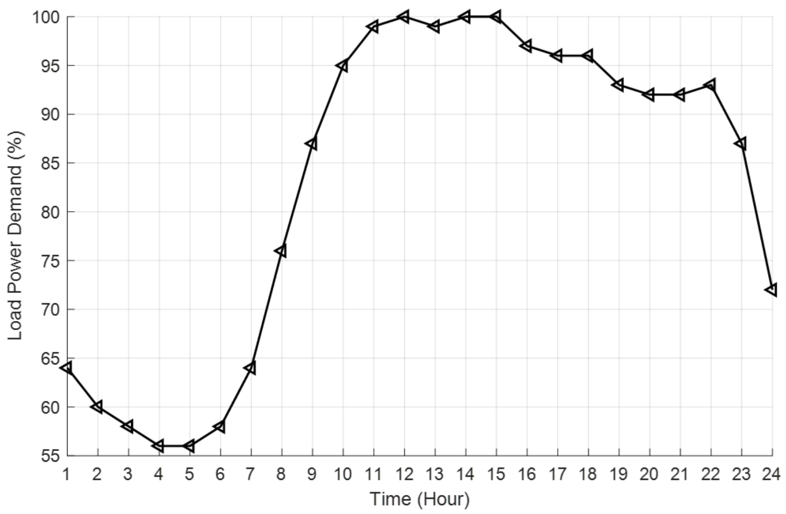


Figure 1. The daily load demand varriation.

III.2. Modeling of PV Uncertainty

The irradiance of solar for each of the day's hours could be modeled by the Beta Probability Density Function (PDF) supported by historical data. For every period (1 h), the PDF irradiance of solar may be defined by [38]:

$$f_b(s) = \begin{cases} \frac{\Gamma(A+B)}{\Gamma(A)\Gamma(B)} s^{(\alpha-1)} & 0 \le s \le 1, \ \ A, B \ge 0 \\ 0 & Otherwise \end{cases} \tag{29}$$

where, *A* and *B* can be calculated as [39]:

$$B = (1-\mu)\left(\frac{\mu(1-\mu)}{\sigma^2} - 1\right) \tag{30}$$

$$A = \frac{\mu \times B}{1-\mu} \tag{31}$$

The solar irradiance state (s) probability for each specific hour could be defined as:

$$P_s\{G\} = \int_{s_1}^{s_2} f_b\,(s)\,ds \tag{32}$$

The output power of the PV module may be expressed as [40, 41]:

$$P_{PV\circ}(s) = N \times FF \times V_y \times I_y \tag{33}$$

$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{oc} \times I_{sc}} \tag{34}$$

$$V_y = V_{oc} \times K_v \times T_{cy} \tag{35}$$

$$I_y = s\left[I_{sc} \times K_i \times (IT_{cy} - 25)\right] \tag{36}$$

$$T_{cy} = T_A + s\left(\frac{N_{OT} - 20}{0.8}\right) \tag{37}$$

The total HRES units' output power-based on the PV panel's irradiance characteristics and specification.

$$P_{PV}(t) = \int_{s_1}^{s_2} P_{PV\circ}\,(s) P_s\{G\}\,ds \tag{38}$$

Figure 2 showed the daily output power generated injected from the PV units, respresented in 24 hours.

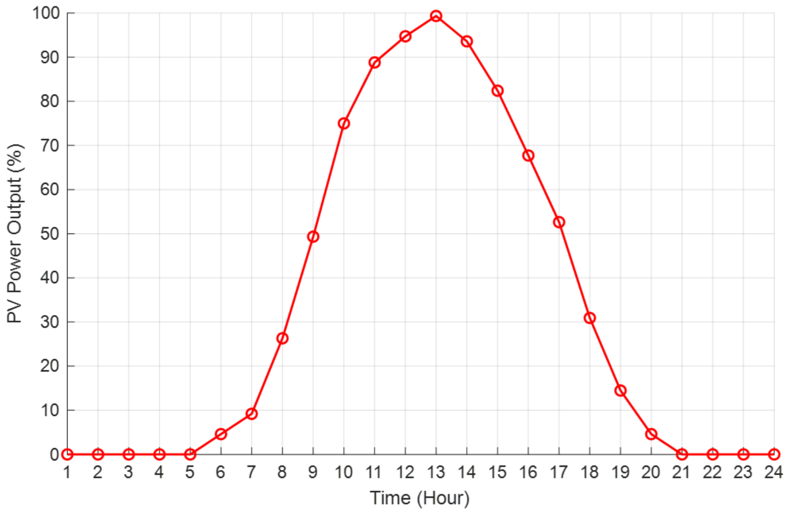


Figure 2. The daily variation of PV output power.

III.3. Modeling of WT Uncertainty

The output power from the wind turbine is related to the parameters of power performance curve and wind speed. Whereas, once the PDF is produced in a specified period segment, the power output in every state may be calculated by the next equation [42, 43]:

$$P_{WT}(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci} \\ P_{rated} \times \frac{(v - v_{ci})}{(v_r - v_{ci})} & v_{ci} \leq v \leq v_r \\ P_{rated} & v_r \leq v \leq v_{co} \\ 0 & v_{co} \leq v \end{cases} \tag{39}$$

Figure 3 showed the daily output power injected from the WT units represented in 24 hours.

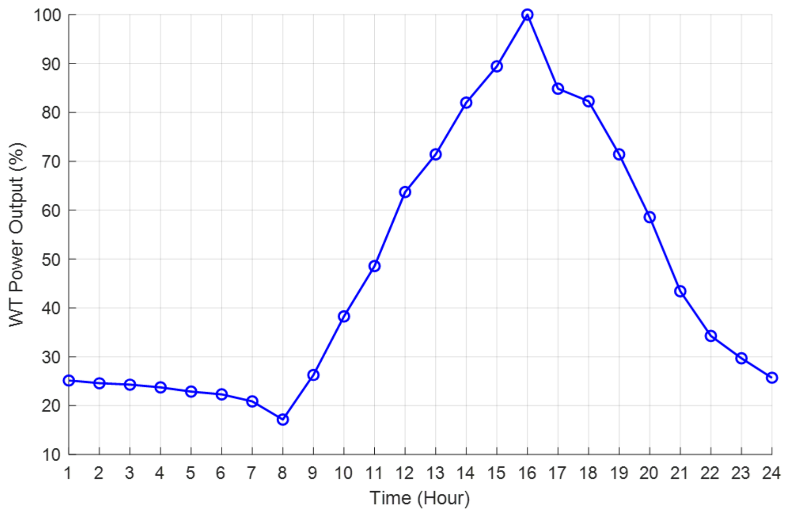


Figure 3. The daily variation of WT output power.

IV. Optimal Design and Analysis Results

The proposed ALO algorithm was tested and validated on the standard medium voltage distribution system IEEE 33-bus, which are represented in figure 4. The base voltage is referred to 12.66 kV and the total demand of loads 3715.00 kW and 2300.00 kVar [44].

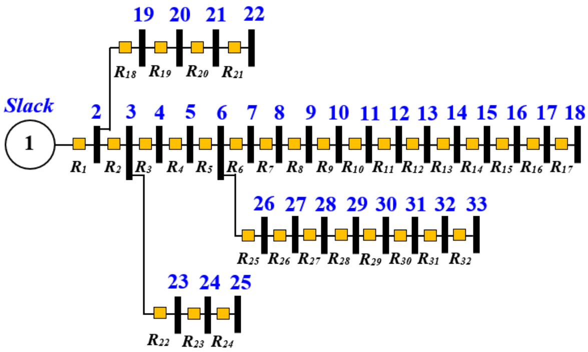


Figure 4. Single diagram of IEEE 33-bus distribution system.

Table 1 contains the daily main characteristics and parameters of the IEEE 33-bus distribution system before HRES units' installation.

Table 1. The daily main characteristics of the distribution system.

Paramaters	Voltage (kV)	Buses	Relays	*TAPL* (kWh)	*TRPL* (kVarh)	*TVD* (p.u.)	*TOT* (sec)
Values	12.66	33	32	3557.02	2412.00	35.65	492.08

Figure 5 demonstrates the convergence characteristics for the MOF minimization after applying the selected algorithm of ALO for the optimal integration of the HRES into test system.

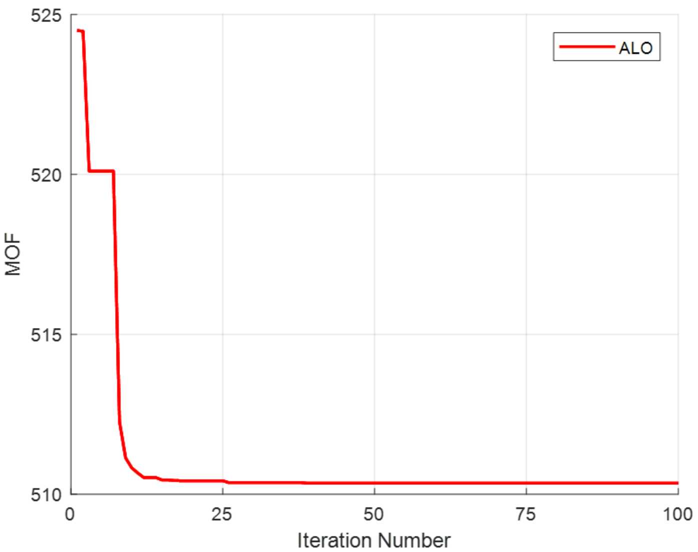


Figure 5. Convergence curve of applied ALO algorithm.

By doing the analysis of the convergence characteristics in the previous figure, when applying the selected algorithm of ALO for HRES's optimal integration in the standard test system, and for a maximum iterations' number equal to 100, a population size of 10, reveals that the ALO algorithm produced very good solutions and results.

The ALO algorithm provided the minimum of MOF until a value of 510.34, including a smooth and a quick convergence characteristic reaching the optimal and best solutions, where it early settles down almost within 40 iterations for the optimal integration of HRES units into the test system IEEE 33-bus.

Tables 2 and 3 summarize all the optimization results after using the ALO algorithm of the optimal placement of HRES into the distribution system and their impact on the system's techno-economic parameters, respectively.

Table 2. Optimal placement results of HRESs in the distribution system.

HRES Number	PVDG		WTDG		
	Bus Location	P_{PV} (kW)	Bus Location	P_{WT} (kW)	Q_{WT} (kVar)
$HRES_1$	4	316.71	3	761.00	540.90
$HRES_2$	5	617.00	9	627.63	459.91
$HRES_3$	6	357.04	14	430.35	309.26

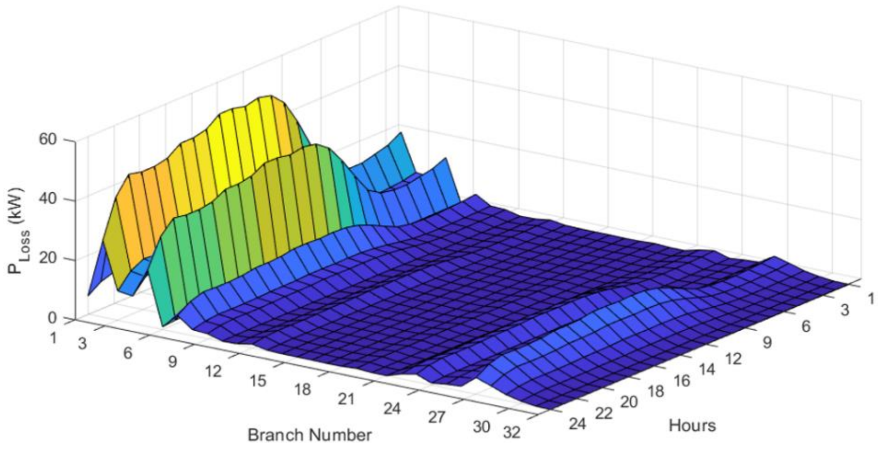
Table 3. The technical and economic parameters with HRES units.

TAPL (kWh)	*TVD* (p.u)	*TOT* (sec)	IC_{PV} (M.$)	IC_{WT} (M.$)	*MOF*
1649.60	20.43	488.69	5.188	7.312	510.34

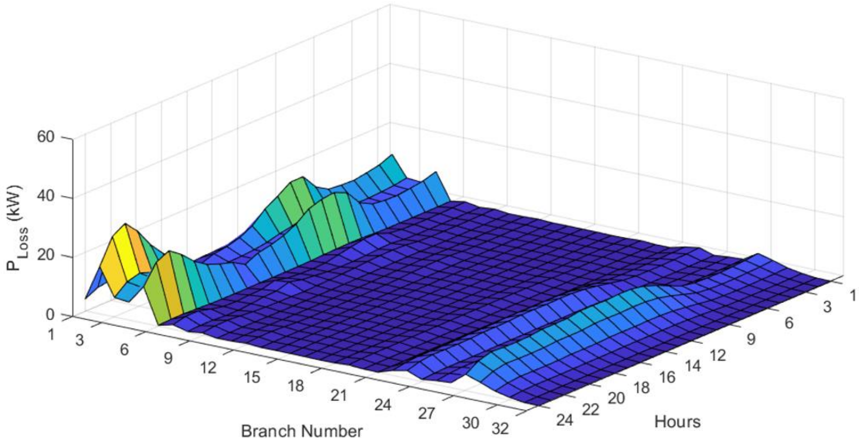
Analyzing the results depicted in Tables 2 and 3 shows that the optimal integration of the HRESs using the ALO algorithm led to very good results of minimizing the MOF until a value of 510.34.

The simultaneous injecting of active and reactive powers from both renewable sources is the reason for those results, where minimized the daily active power losses until 1649.60 kWh comprises a reduction rate of 43.8 %, the daily voltage deviation until a value of 20.43 p.u., the daily operating time of overcurrent relays until 488.69 seconds, including a very favorable investment cost of WT and PV units of 5.188 M$ and 7.312 M$, respectively.

Figure 6 represents the daily branch active power losses variation for the optimal installation of HRES units in the distribution system.



(a)



(b)

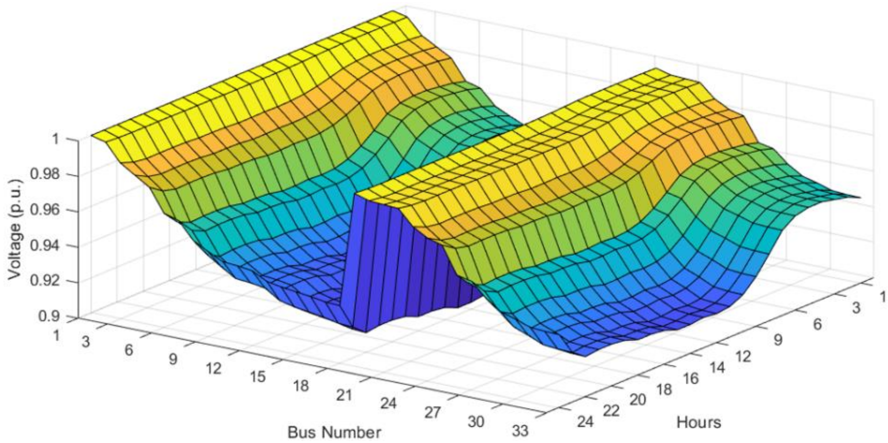
Figure 6. The daily variation of active power losses for distribution system.
(a) Basic case, (b) With HRES.

Clearly, the optimal installation of the hybrid units of HRES caused an obvious effect on the technical parameters of the test system IEEE 33-bus, where among them, the daily active power losses showed in the 3D graphics of Figure 6.

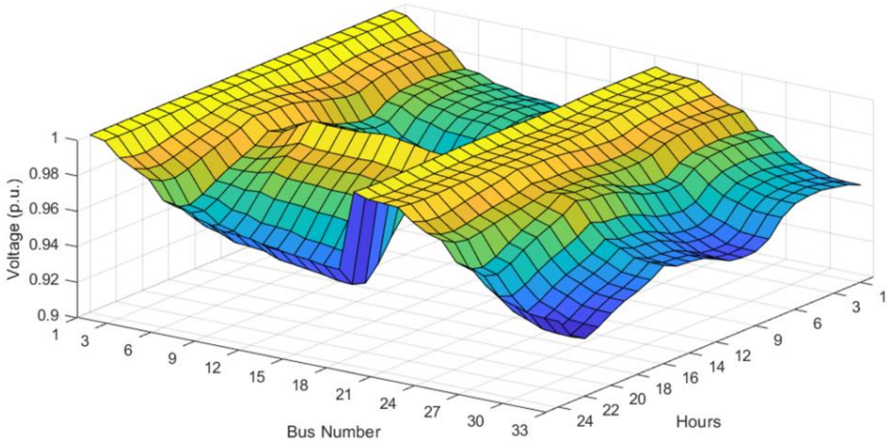
Obviously, the daily active power losses significantly minimized after that optimal presence of the HRES in every branch of the test system and clearly along the day's hours, for reason that the presence of both renewable sources guarantee the generation of both active and reactive powers for all day's hours, where one source compensates the other's absence or weakness.

Another remark is that the total daily active power losses were minimized after that optimal integration from a value of 3557.02 kWh until a value of 1649.60 kWh, including a reduced rate of 43.8 %.

Figure 7 depicted the daily bus voltage profiles variation for the optimal presence of HRES units in the test distribution system.



(a)



(b)

Figure 7. Daily bus voltage profiles variation for distribution system.
(a) Basic case, (b) With HRES.

Based on the results shown in Figure 7, it is clear that the daily bus voltage profiles were enhanced after the optimal installation of HRES units into the test distribution system almost along the 24 hours for reason that the hybrid sources provided both active and reactive generation without any interruptions, especially at mid-day hours, where the voltage profiles were at their best and maximum values, which was synchronous with the pick generation from the PV and WT sources.

Those achievements of the voltage profiles enhancement are directly related to the minimization of total voltage deviation after that optimal integration of HRES units, from a value of 35.65 p.u. until 20.43 p.u. with a reduced rate of 57.30 %, whereas represented and mentioned in previous equation (4), the voltage deviation is known as the difference between the referenced value of 1 p.u. and the actual value of the voltage at buses.

Figure 8 demonstrates the daily operating time variation of the overcurrent relays for HRESs' optimal presence in the distribution system.

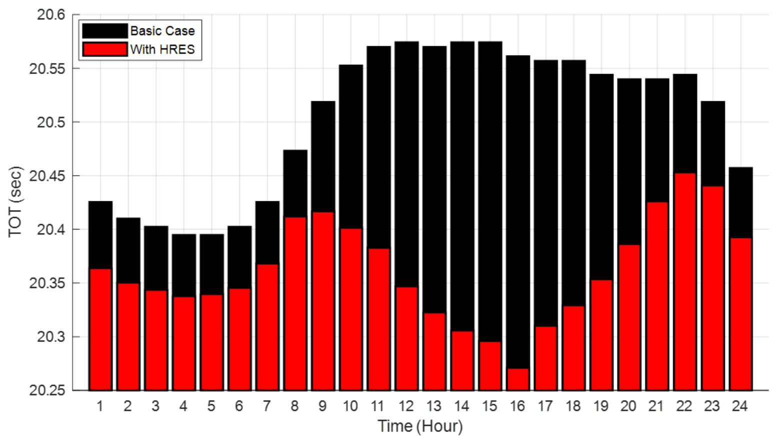


Figure 8. Daily total operation relays for distribution system.

The main function of the overcurrent relays is to detect and identify the fault current which occurs through the distribution lines, and follow it by the quick separation and removal, in order to protect of the targeted parts of system. Minimizing that operating time is considered so beneficial in different aspects, as extending the equipment's lifetime of the system and maintaining the continuity of service.

Applying the ALO algorithm to minimize the MOF for the optimal installation of the HRES in the standard of test, clearly drove to the reduction of the daily overcurrent relays' operating time from a value of 492.08 seconds at the basic case until a value of 488.69 seconds, where obviously the generation of both active and reactive powers from the hybrid sources is the principal reason for those superior and better results and achievements.

V. Conclusions

This paper was devoted to the analysis of the MOF minimization which was represented as the total of different techno-economic parameters of TAPL, TVD, TOT, ICPV, and ICWT, when optimally allocating the HRES based on renewable sources PV and WT in the standard test system IEEE 33-bus, using a recent nature-inspired metaheuristic algorithm of ant lion optimizer, taking into consideration the daily uncertainties of load-RES source power variation.

The ALO algorithm revealed very good behavior and effectiveness when providing the finest results of MOF minimization, including quick convergence characteristics.

The simulation results clarify the efficiency of the optimal HRES's presence while providing a strong enhancement of the test system's performance, as a result reducing the active power losses by 43.8 %, improvement of the voltage profiles by minimizing the voltage deviation by 57.30 %.

Also, clearly enhanced the protection system against the overcurrent, including a very favorable investment cost for both power sources of PV and WT of 5.188 M$ and 7.312 M$, respectively. For reason that the hybrid sources were capable to inject the active and reactive powers simultaneously almost along the day's hours with no interruptions.

Lastly and when based on the previous discussions and results, it is recommended to apply the hybrid sources of PV and WT to the practical distribution grids for their huge technical merits.

The future work will focus on implementing different hybrid sources in the distribution grid to improve its performance when considering the seasonal uncertainties of the load-source power variation, and especially concentrating on ameliorating the protection system against the overcurrent.

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