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Article



An Effective Bi-Stage Method for Renewable Energy Sources Integration into Unbalanced Distribution Systems Considering Uncertainty

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Abstract: The output generations of renewable energy sources (RES) depend basically on climatic conditions, which are the main reason for their uncertain nature. As a result, the performance and security of distribution systems can be significantly worsened with high RES penetration. To address these issues, an analytical study was carried out by considering different penetration strategies for RES in the radial distribution system. Moreover, a bi-stage procedure was proposed for optimal planning of RES penetration. The first stage was concerned with calculating the optimal RES locations and sites. This stage aimed to minimize the voltage variations in the distribution system. In turn, the second stage was concerned with obtaining the optimal setting of the voltage control devices to improve the voltage profile. The multi-objective cat swarm optimization (MO-CSO) algorithm was proposed to solve the bi-stages optimization problems for enhancing the distribution system performance. Furthermore, the impact of the RES penetration level and their uncertainty on a distribution system voltage were studied. The proposed method was tested on the IEEE 34-bus unbalanced distribution test system, which was analyzed using backward/forward sweep power flow for unbalanced radial distribution systems. The proposed method provided satisfactory results for increasing the penetration level of RES in unbalanced distribution networks.

Keywords: renewable energy resources; climatic conditions; multi-objective cat swarm optimization; unbalanced distribution systems; voltage control devices

1. Introduction

Renewable energy sources (RES) units have the potential to replace conventional energy sources in electrical power systems because of their environmental and technical merits, especially with the variations in fossil fuel prices and their non-renewability. These reasons motivated decision-makers to increase the RES penetration level in distribution systems. However, the high penetration of RES in distribution systems may have negative effects on the voltage profile, especially when the RES uncertainty nature is considered. In [1], the authors discussed the operational and reliability issues that resulted from the high penetration of PN generation can be mitigated using reactive power from step voltage regulators [2]. The authors of [3] discussed the overvoltage and overcurrent problems due



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). to grid-connected PV systems under different penetration levels. Moreover, the authors of [4] proposed different oscillation mitigation controllers to overcome the fluctuation caused by wind power using time-domain simulations.

Therefore, it became an urgent need to examine the impact of RES penetration on the distribution system voltage. The impact of PV penetration on the system voltage under various penetration scenarios was presented in [5]. Further, [6] presents an optimization-based methodology that can determine the maximum penetration level of RES without exceeding the limits of voltage fluctuation considering load uncertainty. In [7], maximizing the Distributed Generation (DG) capacity without causing overvoltage was considered as the main objective of the RES hosting capacity problem in the distribution network. Recently, due to the quick development of metaheuristic optimizations, they are applied to adapt the voltage control setting of the RES penetration to regulate the voltage profile, for example, the closed-loop particle swarm and elephant herd optimizer [8], efficient analytical method integrated with the optimal power flow algorithm [9], water cycle algorithm [10], fuzzy logic integrated with artificial neural networks [11], and different machine learning algorithms [12].

In this regard, [13] proposed a method based on the cat swarm technique that was presented for minimizing the voltage fluctuations and preserve the voltage profile through its limit that is caused by RES in the distribution system. Moreover, in [14] different penetration levels of RES were studied in a real distribution system using open distribution system simulator. Moreover, in [15] the authors increased the penetration levels of RES to 50% of the total demand where the DG units have small sizes. Also, the effect of penetration level on the system voltage was simulated and analyzed. In [16], diverse approaches for voltage profile regulation and voltage unbalance reduction were demonstrated with rising the penetration level of rooftop photovoltaic systems in distribution feeders. The authors in [17] proposed a method for obtaining the maximum allowable power from RES without causing voltage violations while neglecting the RES uncertainty. In [18], the distributed energy storage was used to mitigate the voltage fluctuation problem caused by PV generation sources. In [19], reducing the voltage fluctuation problem in distribution networks was employed considering high penetration of PV systems by using customer-side energy storage systems. Coordination and optimal sitting of voltage control devices was an effective method for mitigation voltage problems, especially those due to RES in distribution systems as discussed in [20]. In [21], the allocation of renewable energy resources considering network reconfiguration was carried out optimally by using the equilibrium optimization algorithm. In [22], an optimal approach for of automated operation of distribution systems was carried out by using a manta ray optimizer. In [23], a coordinated approach between various enhancement devices for power system operation was employed involving the existence of renewable energies, fixed capacitor banks, and voltage regulators. In that work, an enhanced grey wolf optimizer was employed for finding the optimal co-ordination. Minimizing the investment costs of these coordinated devices and minimizing the active power losses were the economic and technical issues considered in [24]. The techno-economic issues were considered also in [25] to enhance the performance of distribution systems. The fluctuations of voltage and uncertainty were of low interest in most work described in the literature.

To solve the operational problems with RES, different penetration strategies for RES in an unbalanced distribution system were considered. Specifically, a bi-stage planning model was proposed for optimal allocation of RES penetration. In the first stage, the optimal RES locations and sites to minimize the voltage variations in the distribution system were investigated. In turn, the second stage aimed to obtain the optimal setting of the voltage control devices to regulate the voltage profile. For this purpose, the multiobjective cat swarm optimization (MO-CSO) algorithm was developed to solve the bistages optimization model for improving the distribution system performance. The impact of RES penetration level and their uncertainty on the distribution system. The results showed that the proposed method can provide effective solutions while increasing the RES penetration level in radial unbalanced distribution systems. The novelties of the current paper can be summarized as follows:

- o The impact of the RES (PV and wind) penetration levels on distribution systems are studied;
- o A bi-stage procedure is proposed to improve the system performance and reduce the system voltage fluctuation due to RES;
- o The proposed method aims to determine the optimal placement and sizing of RES and the optimal setting of the system voltage control devices in order to maximize the benefits of the RES penetration and minimize the variation in the system voltage;
- o The MO-CSO algorithm is combined with an unbalanced power flow method in order to analyze the system and solve the optimal placement and sizing problem.

All the analysis and simulations were implemented under the MATLAB environment. This paper is arranged as follows: Section 2 discusses the voltage control devices; Section 3 describes cat swarm optimization algorithm; Section 4 presents the impact of RES penetration level on voltage profile; Section 5 describes the proposed bi-stage method; Section 6 summarizes and discusses the calculated results; Section 7 presents the conclusion.

2. Voltage Control Devices

Voltage control devices are extensively utilized in distribution networks to solve voltage problems. However, there is a need for determining the optimal placement and setting of these devices. In this section, the most common control devices that are used in this paper are described.

2.1. Static VAR Compensator (SVC)

Static VAR compensator (SVC) is considered an effective flexible alternating current transmission (FACTS) unit that is used in both transmission and distribution systems. It has a fast response in controlling the voltage. It usually consists of banks of capacitors and reactors controlled by Thyristors, as displayed in Figure 1. SVC devices are usually used for damping the voltage oscillations and improving the system voltage as they can inject or absorb reactive power from the system [26].



Figure 1. Block diagram of static VAR compensator (SVC).

2.2. Transformer Tap Changer (TTC)

Transformer tap changers (TTCs) are widely used to control the voltage of the transformer secondary side to preserve it within its allowable limits. The voltage control in this type depends on varying the position of the transformer taps. However, this type of voltage control is limited by a specified range of taps [27]. A tap changer unit is useful since it can adapt the number of turns on a particular transformer side, thereby altering the transformer ratio. Typically, this tab setting can be adjusted between 10 and 15% in steps of 0.6-2.1%.

2.3. Distribution Voltage Regulators (DVRs)

Distribution voltage regulators (DVRs) are used to regulate the voltage and keep it almost constant. Voltage regulators are basically step-type autotransformers with a preventive transformer and a switch, to obtain a regulation voltage range of $\pm 10\%$ [20].

3. Cat Swarm Optimization (CSO) Algorithm

The CSO algorithm is one of the latest optimization techniques that can be used for solving single- and multi-objective optimization problems. This algorithm simulates the strategy of cats when hunting. In the strategy of cats for hunting their victims, their movements are divided into two modes (seeking mode and tracking mode). Cats at seeking mode collect data about the surroundings (search space) and move carefully with slow steps. In contrast, cats in tracking mode move and jump very fast to catch the victim [28]. These two modes are simulated in the optimization algorithm by applying several iterations until the convergence criteria is satisfied as described in [29].

A solution of an optimization problem is determined by getting the values of some controlled variables (X1, X2, X3...) that give the optimal solution of the fitness function (objective = f (X1, X2, X3...)). Thence, arbitrary solutions are assumed, where each solution is defined as a cat. Note that cats are nominated randomly to be in seeking or in tracking modes. A tracking cat modifies its controlled variables in its solution as follows:

$$v_{new} = w * v_{old} + c * r \left(CVV_{global \ best} - CVV_{old} \right)$$
(1)

$$CVV_{new} = CVV_{old} + v_{new} \tag{2}$$

A seeking cat adapts its value by making some copies of its solution and change counts of dimensions in each copied solution by the following equation:

$$new value = old value \pm rand * SRD * old value$$
(3)

Then, it selects the best value among these updated copies to be considered as a new solution.

4. Impact of RES Penetration Level on Voltage Profile

4.1. RES Uncertainty Representation

The fluctuations of output power from the RES are dependent on climatic conditions. The outputs of the wind turbine (WT) and photovoltaic (PV) are dependent on the wind speed and solar irradiance, respectively, as follows:

$$P_{W}(V_{W}) = \begin{cases} P_{rated} \times \frac{V_{W} - V_{ci}}{V_{r} - V_{ci}} & V_{ci} \leq V_{W} \leq V_{r} \\ P_{rated} & V_{r} \leq V_{W} \leq V_{co} \\ 0 & V_{ci} \geq V_{W} & OR & V_{W} \geq V_{co} \end{cases}$$
(4)

$$P_{PV}(G) = \begin{cases} \frac{P_{rated} \times G^2}{G_{std} \times G_C} & 0 < G \le G_C\\ \frac{P_{rated} \times G}{G_{std}} & G_C < G \le G_{std} \end{cases}$$
(5)

When the output power of the DG units fluctuates, the system voltage also fluctuates [30]. Consequently, the system voltage can fluctuate between the highest and lowest voltage profiles. The highest level has occurred when all DG units generate their maximum output, and this happens under the best generation conditions (most extreme wind speed and solar irradiance) [31]. Contrarily, the lowest voltage profile occurs when all DG units generate their minimum output (no output), and this happens under the worst generation conditions (minimum wind speed and solar irradiance) [6].

4.2. Influence of RES Penetration on System Voltage

The IEEE 34-bus test distribution system [32], which is unbalanced, was considered to be the system under study, see Figure 2. This test system represents a real unbalanced distribution system in Arizona. The feeder's rated voltage equals 24.9 kV, with a total power loss of 285.47 kW. The substation transformer of the system has a tap changer that controls the transformer voltage between 0.9 and 1.1 p.u. Two voltage regulators are installed in the system between buses 7–8 and 19–20, and they can operate with 32 steps ranging from 0.9 to 1.1 p.u.



Figure 2. IEEE 34-bus unbalanced distributed system.

For approving the concept that the system voltages fluctuate between the highest and lowest voltage profiles, one-year climate conditions data were applied for two PV units (at bus 4 and 27) and one WT unit (at bus 20) with a rated power of 294.97 kW for each unit to achieve 50% penetration level. The climate conditions data are shown in Figure 3. Using Equations 4 and 5 for calculating RES outputs at each hour and performing load flow calculations at each hour, the system voltage profiles can be obtained, as shown in Figure 4. It is clear that all system voltage profiles all over the year lie between the highest voltage profile (rated output from RES) and the lowest voltage profile (no output from RES).

The output power of the RES units is uncertain and difficult to be controlled, as it depends on the climatic conditions [33,34], so two penetration strategies were considered to study the effect of the RES penetration level on the system voltage.

In the first stage, the effect of the RES penetration level on the voltage profile was studied considering a fixed placement of the RES in the system, and the only change was in the penetration level, which follows fixed percentages (25%, 50%, and 75%) from the total demand at buses (4, 20, 27), as shown in Table 1. In the second stage, the main objective was to study the effect of DG location rather than the effect of the DG penetration level. Thus, we fixed the penetration level at 75%, and the same trends can be obtained for the other penetration levels (i.e., 25% and 50%).

Table 1. Renewable energy sources (RES) planning for different penetration levels.

Penetration Level	Case 1 (25%)	Case 2 (50%)	Case 3 (75%)
Output power from each unit	147.485 kW	294.970 kW	442.467 kW



Figure 3. One-year climate conditions data; (a) solar radiation, and (b) wind speed.



Figure 4. System voltage profiles all over the year for 50% penetration level.

In the second strategy, the effect of RES placement on the voltage profile was studied considering a fixed penetration level (75% from total demand). Therefore, the placement of the RES was varied randomly corresponding to four cases as shown in Table 2. To study the voltage behavior under these cases, load flow calculations were performed twice in

each penetration case, the first load flow calculation was at the highest DG generation output, and the second one was at the lowest DG generation output. After applying the backward-forward load flow calculations described in [35–37], the following results were obtained.

Penetration Level	Cases	First RES Bus	Second RES Bus	Third RES Bus
0%	Case 0	No	o output from any R	RES
75%	Case 1	4	20	27
	Case 2	9	23	31
	Case 3	2	3	4
	Case 4	25	30	31

Table 2. RES placement for different cases of the second strategy.

As presented in Figure 5, which represents the system voltage profiles after applying the first strategy, it can be seen that the voltage variation increases with the increase of penetration level percentage, and it is also observed that in all cases, the voltage profiles exceeded the permissible limits.



Figure 5. Voltage profiles for different penetration levels.

After applying the second strategy, considering the penetration level to be 75% from the total demand and changing the generation buses according to the cases in Table 2, it was observed that the voltage variation changed when changing the generation buses as depicted in Figure 6; however, the penetration level was fixed. These results show that

- RES penetration in the distribution system causes voltage variation in the system buses due to the uncertainty operation of RES;
- Voltage variation does not only depend on the RES penetration level, but also the placement of DG units may have a significant effect on the voltage variation percentage.



Figure 6. Voltage profiles of the second strategy.

5. The Proposed Bi-Stage Method

5.1. Method Description

A bi-stage method was proposed to obtain the maximum benefits from the RES, keep the system voltage within limits, and reduce the system voltage variations due to RES as follows.

In the first stage, the optimal placement and sizing of RES units were obtained by using the MO-CSO procedure, where the objectives of this problem were minimizing voltage fluctuation (*OF1*) and system power losses (*OF2*) without considering the voltage limits. Thence, the problem was considered as a multi-objective optimization problem represented by the weighted sum approach for objective functions as follows:

$$OF1 = Min \frac{\sum_{i=1}^{n_{bus}} \left(S_{load_i} * \sqrt{\left(V_{high_i} - V_{low_i} \right)^2} \right)}{\sum_{i=1}^{n_{bus}} S_{load_i}}$$
(6)

$$OF2 = Min \sum P_{loss} \tag{7}$$

where,

$$P_{loss}/phase = \sum_{i=1}^{n_{lines}} P_i^{in} - P_i^{out}$$
(8)

$$FF = w1 * \frac{OF1}{OF1_{Max. value}} + w2 * \frac{OF2}{OF2_{Max. value}}$$
(9)

Subject to:

$$\sum PG - P_{loss} = P_d \tag{10}$$

$$bus_2 \le place \ _{DDG} \le N_{buses} \tag{11}$$

In the second stage, the goal was to improve the voltage profile and keep it within the permissible limits. So, the fitness function (*FF*) can be described as follows:

$$FF = Min \sum_{i=1}^{n_{bus}} \left(\frac{v_i^{mean} - v_i^{specific}}{v^{Max} - v^{Min}} \right)^2$$
(12)

where,

$$v_i^{mean} = \frac{v_i^{highest} - v_i^{lowest}}{2} \tag{13}$$

This fitness function can be achieved by obtaining the best adjustment of the voltage control devices, e.g., voltage regulators and Distribution Flexible Alternating Current Transmission System (D-FACTS) units using the CSO algorithm.

5.2. Application of Proposed Two-Stage Method to IEEE 34-Bus Distribution System 5.2.1. First Stage

The optimal allocation and sizing of RES units can be achieved according to the following steps.

Step 1: creating random solutions, in which each solution is defined as a cat. The controlled variables of each solution are the placement and the output of n DG units. Solutions matrix (RS) will be as follows:

	1	DG_1^{place}	•••	DG_n^{place}	DG_1^{power}		DG_n^{power}	
PC_	÷	:		:	÷	•••	÷	(14)
K3 — {		÷		:	:	•••	÷	(14)
	прор	Ŀ		:	:		:	

Step 2: For each cat, obtaining the load flow solution under the worst and the best generation conditions, then Equation (10) is applied to calculate the normalized fitness function for this solution.

Step 3: Finding the best cat solution that has the minimum objective function.

Step 4: Applying the developed CSO method to construct a new set of cats' values.

Step 5: Repeating the abovementioned steps from 2 to 4 until convergence criteria is satisfied.

5.2.2. Second Stage

In this stage, the voltage control devices will be adjusted to control the voltage. The control variables in this problem are the substation tap changer setting, tap setting of the two voltage regulators, placement of one SVC, and the reactive power of the SVC. The problem can be solved by applying the following steps:

Step 1: Creating random solutions, where each solution represents a cat.

	1	Vsub	Tab(VR1)	Tab(VR2)	<i>Place_{svc}</i>	Qsvc	
$RP = \langle$	÷	÷	:	÷	÷	÷	(15)
	прор	Ŀ	•			÷	

Step 2: For every cat solution, power flow analysis is conducted under worst and best generation conditions considering the regulating voltage devices adjustment contained in this cat solution, then the following equations are applied to calculate the fitness function (*FF*) for this solution [38].

Step 3: Examining that all bus voltages in all generation circumstances are within their boundaries as mentioned in Equation (17); if any cat is not satisfying the constraints, the solution will be eliminated.

$$V_i^{\min} \le V_i \le V_i^{\max} \ i = 2, 3, \dots nbus \tag{16}$$

Step 4: Finding the best cat solution that has the minimum objective function.Step 5: Applying the developed CSO method to build a new set of cats' values.Step 6: Repeating the above steps from 2 to 5 until reaching the convergence criteria.The procedure of each stage [13] of the proposed method is described in Figure 7.



Figure 7. Flowchart of each stage in the proposed algorithm.

6. Simulation Results and Discussion

6.1. First Stage Results

The first stage of the proposed method was applied, and the results in Table 3 were obtained. The results show that some DG units should be located at buses near the substation (buses 2 and 3) to minimize the voltage fluctuation, and other units should be located at highly loaded buses (buses 20 and 27) to minimize the losses. The power loss after applying this stage solution was reduced by 15.9% from the base case, as the power loss of the highest voltage profile (RES generates its maximum output) was 239.93 kW. However,

the reduction in power loss seems to be not high, which is logical, as minimizing the voltage fluctuation takes more priority than minimizing losses. Therefore, the voltage fluctuation was minimized between the two voltage profiles, as revealed in Figure 8. Further, the value of the voltage profile index was high (28.7646), as the voltage constrain was not considered in this stage, and the values of system buses voltages are far from 1 p.u.

Table 3. Results of the first stage (placement and sizing of RES units results).

Bus Number	3	27	20	2
DG Generation at Best Condition (kW)	176.09	83.43	94.98	962.09



Figure 8. Voltage profiles after optimal placement and sizing of RES units.

6.2. Second Stage Results

After applying the second stage steps, the optimal adjustment of the voltage control devices was obtained and is shown in Table 4. In this stage, the voltage fluctuation was minimized in all phases, and the voltage profiles became within limits, as shown in Figure 9. The value of the voltage profile index was reduced to be 1.6663, as the values of system buses voltages were close to 1 p.u. System losses after applying the second-stage solution increased slightly to be 246.93 kW at the highest voltage profile and 296.11 kW at the lowest voltage profile. Moreover, the voltage fluctuation index increased slightly to be 0.0481. The values of the objective functions in the two stages are summarized in Table 5. Thence, the proposed method can be considered as an effective method in RES planning that maximizes the benefits of RES integration and maximizes RES penetration level by solving the penetration uncertainty problems on system voltages.

Table 4. Voltage regulating devices setting in the second stage.

Device	Adjustment
Substation transformer	1.023 p.u.
VR1 tap	9
VR2 tap	14
SVC bus	21
QSVC	200 KVar





Stage	First Stage	Second Stage
P _{loss} of the lowest voltage profile (kW)	285.47	296.11
P _{loss} of the highest voltage profile (kW)	239.93	246.93
voltage fluctuation index (OF1)	0.0437	0.0481
voltage profile index (FF)	28.7646	1.6663

 Table 5. Objectives values after applying the first and second stages.

7. Conclusions

In this paper, the impact of RES penetration level and its uncertainty problem in distribution systems were studied by using the CSO algorithm and backward-forward sweep power flow. The study results have the following outputs:

- RES uncertainty causes voltage variation to the distribution system voltage profile and makes the voltage profile exceed the limits;
- Voltage variation depends not only on the RES penetration level but also on the placement of DG units;
- The paper proposed a bi-stage method based on the CSO algorithm for minimizing voltage variation and power loss, and improves the system voltage profile considering the uncertainty of RES units;
- The first stage was concerned with the placement and sizing of RES units. It succeeded in reducing the power loss by 15.9% and minimizing the voltage fluctuation index to be 0.0437;
- In the second stage, the voltage control devices including voltage regulators and SVC were adjusted by the optimization technique for improving the voltage profile. It succeeded in reducing the voltage profile index to be 1.6663, with a 94.2% reduction from the first stage, while the improvements achieved in the first stage were maintained;
- The proposed RES integration method was tested on unbalanced IEEE 34-bus radial system networks under uncertainty conditions, which provided satisfactory results for increasing the RES penetration level.

In future work, it will be beneficial to consider the regulatory framework to attract RES projects in selected optimal distribution network nodes, for example, the simultaneous framework for penetration of RES and the planning procedure for the expansion distribution network considering the impact of varied strategies of demand response. Also, we will investigate the optimal penetration of RES considering distribution networks reconfiguration. **Author Contributions:** All authors have contributed to the preparation of this manuscript. E.S.A. and R.A.E.-S. designed the idea strategy, studied the data, and wrote the manuscript. M.M.F.D. and K.M. revised and proofread the manuscript and designed some figures. Finally, A.A.A.E.-E. and M.L. were in charge of reviewing, editing, funding, and supporting different improvements for the manuscript. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

CVV	Control variable value
D-FACTS	Distributed flexible AC transmission system
DG	Distributed generation
SVC	Static VAR compensator
WT	Wind turbine
PV	Photovoltaic
FF	Fitness function
OF	Objective function
r	Random number between 0 and 1
v _{new}	New cat speed
v_{old}	Old cat speed
VF	Voltage variation between the highest and lowest voltage profiles
w	Weighting factor
PG	Generated power
P_D	Demand load power
Ploss	Power loss
P_i^{in}	Input active power of section <i>i</i>
P_i^{out}	Output active power of section <i>i</i>
Sload	Total demand load
n _{pop}	Number of populations
n _{bus}	Number of buses
VR	Voltage regulator device
V _{highi}	Highest voltage at bus <i>i</i>
V _{lowi}	Lowest voltage at bus <i>i</i>
ΔV	Voltage difference between highest and lowest voltage profiles
VR_{TAP}	Voltage regulator taps setting.
Q_{svc}	SVC reactive power.
G	Solar insolation (kW/m^2)
G_{std}	Standard solar insolation (1 kW/m^2)
G_C	Certain irradiance point (0.12 kW/m^2)
Prated	Rated power
V_W	Wind speed(m/s)
V_r	Rated wind speed
V _{ci}	Cut-in wind speed
V_{co}	Cut-out wind speed

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