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Practical Considerations for Optimal Conductor Reinforcement and Hosting Capacity Enhancement in Radial Distribution Systems

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ABSTRACT The high penetration level of distributed generation (DG) units may lead to various problems and operational limit violations in electric power distribution systems if it exceeds a particular limit known as the system's hosting capacity (HC). In this paper, the problem of selecting the optimal conductor for a real radial distribution system in Egypt is investigated using a recent meta-heuristic algorithm, known as salp swarm optimization. First, a constrained optimization problem is introduced to minimize the combined annual cost of energy losses and the investment cost of the conductors while complying with the system voltage limits and conductor thermal capacities. The results obtained show the effectiveness of the algorithm in satisfying the objective function and constraints. However, the optimization results also show that a reduction in the size of some existing conductors should take place, although this is not allowed by the utilities because of practical reasons such as load growth, variations in loading scenarios, and the possibility of connecting DG units with uncertain penetration levels and locations. Hence, a practical feeder reinforcement approach is proposed to maintain the constraints while considering these uncertainties. Further, a novel feeder reinforcement index is proposed to assist the distribution system operators and planners to determine the feeders that first need to be reinforced. The results obtained show that the proposed reinforcement approach attains a better level of HC than can be obtained with the conventional conductor selection approach under the same testing conditions.

INDEX TERMS Distributed generation, hosting capacity, optimal conductor selection, optimization, penetration level, power loss reduction, power quality, reinforcement.

I. INTRODUCTION

Nowadays, it is not an easy task for network planners and operators to design an electrical distribution system that is capable of handling load alteration and growth while paying attention to uncertain penetration levels and locations of distributed generation (DG) units that may be connected to the system [1], [2].

DG systems play a vital role in current power systems due to their technical, economic, social, and environmental merits. Despite benefits, there are some problems, especially with excessive DG penetration that may lead to various problems and operational limit violations if it exceeds a particular limit known as the system's hosting capacity (HC). In its broadest scene, HC represents the maximum capacity of DG units that can be integrated into a system while allowing it to function in its intended manner without significant loss of performance. HC is a specific, measurable, practical, and fair power system-oriented concept that uses clear performance indices (a set of technical parameters) as evaluation criteria for assessment of DG penetration.

In the literature, the idea of selecting the optimal conductor sizes had been investigated years ago [3]–[5]. The concept of selecting Aluminum Conductor Steel Reinforced (ACSR) sizes based on economic considerations was introduced in [3]. Later, various optimization techniques such as analytical, numerical, and heuristic-based methods were used to solve the problem of optimal conductor size selection [6]–[10]. However, throughout these studies, one can note that the

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optimal conductor selection problem is always thought of as a solution for power loss reduction in distribution systems without considering today's challenges with the connection of DG units and the problems that have arisen with them. Accordingly, much consideration must be given to obtaining criteria for designing a practical system that is able to handle the different load uncertainties and DG penetration variations.

Distribution system operators (DSOs) in the electricity market are frequently requested to investigate various solutions to ensure that networks are capable of handling these booming DG units in a safe and reliable manner. In this regard, reinforcement of feeders (which means using larger conductor sizes that have lower electrical resistance) is one of the effective techniques that can be used, especially in congested systems, to support the voltage profile, attain better HC, enhance power quality performance, and reduce network losses while increasing the ability to handle more DG penetration. However, feeder reinforcement is not free and certainly will incur extra conductor and installation costs.

In this paper, the optimal conductor selection problem for a real radial distribution system in Egypt is investigated using a recent meta-heuristic algorithm, known as salp swarm optimization (SSO). First, a constrained optimization problem is introduced to minimize the combined annual cost of energy losses and the investment cost of the conductors while complying with the system voltage limits and the thermal capacity of the conductors. As a reduction in the size of conductors is not allowed by utilities due to the practical considerations of load alteration, load growth, and the possibility of connecting DG units with uncertain penetration levels and locations, therefore a practical feeder reinforcement approach is proposed to maintain the constraints while considering these uncertainties. In addition, a novel feeder reinforcement index (*FRI*) is proposed as a sensitivity index to determine the feeders that need to be reinforced first. The proposed *FRI* can be easily employed to select the candidate branches for reinforcement, thus reducing the search space of the problem and consequently speeding up the optimization algorithm.

The rest of the paper is organized as follows: Section 2 presents the conventional optimal conducting problem. Section 3 introduces the proposed practical reinforcement approach and the *FRI* index. The mathematical formulation of the optimization problem is detailed in Section 4. In Section 5 the simulation results are presented and discussed, and finally, Section 6 presents the conclusions, recommendations, and limitations of our study in addition to a preview of future studies.

II. CONVENTIONAL OPTIMAL CONDUCTOR SELECTION APPROACH

In conventional optimal conductor selection approaches, a constrained objective function to minimize a combination of the annual cost of energy losses and the investment cost of the conductors is formulated while complying with the system voltage limits and thermal capacities of the conductors [3]–[10]. The optimal conductor sizes are selected from a set of conductor inventories that include types, electrical and mechanical properties, and sizes of every conductor. Mathematically, the total cost (C_{total}) describes the total economic cost of using a reference conductor of type y for feeder x expressed as a combination of the annual cost of energy losses (C_{loss}) and the investment cost (C_{inv}):

$$C_{total}\left(x,y\right)=C_{loss}\left(x,y\right)+C_{inv}\left(x,y\right) \tag{1}$$

C_{loss} is usually given in terms of the active power loss (P_{loss}) of a branch under peak load conditions, loss factor (LSF), and energy tariff parameters, namely cost of peak demand power loss (k_p) and cost of energy losses (k_e), in addition to the number of hours per year (T) and is expressed as:

$$C_{loss}\left(x,y\right)=P_{loss}\left(x,y\right)\times\left[k_p+\left(k_e\times LSF\times T\right)\right] \tag{2}$$

Consequently, the total annual cost of energy losses ($C_{loss,t}$) of all conductors in a system that is comprised of b branches with n conductor types is expressed as:

$$C_{loss,t}=\sum_{x}^{b}\sum_{y}^{n}P_{loss}\left(x,y\right)\times\left[k_p+\left(k_e\times LSF\times \mathrm{T}\right)\right] \tag{3}$$

Also, C_{inv} is defined in terms of the interest and depreciation factor (IDF) that depends on interest rate (i), lifetime of conductors (F), length of the branch (l), and investment cost of the conductor per unit area per unit length (IC), thus:

$$C_{inv}\left(x,y\right)=IDF\times l\left(x\right)\times IC\left(y\right) \tag{4}$$

$$IDF=\frac{i(i+1)^F}{(i+1)^F-1} \tag{5}$$

The result is an optimized system that utilizes a set of optimal conductors with different sizes. Although this is acceptable in the initial planning stages of electric power distribution systems prior to actual execution, it is not acceptable for running systems. This is because, in most cases, it is not practical to allow replacement of an existing feeder with another one that has a smaller cross-sectional area even if this replacement could reduce the overall system losses. Unfortunately, this practical perspective is not considered in many studies [6]–[9]. To redress this gap, a feeder reinforcement approach is proposed in this study.

III. FEEDER REINFORCEMENT APPROACH

The main target of solving a conventional optimal conductor selection problem is to minimize the total cost for certain conductors that consists of two opposing cost functions, namely C_{loss} and C_{inv}. As illustrated in Fig. 1, for any conductor, when its size increases, the cost of power loss decreases while the cost of investment increases. This process continues until reaching an intersection optimum

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point (A_{opt}). To act in accordance with the design target, network planners tend to optimize the conductor sizes such as (A_1 or A_2) to reach A_{opt} via either conductor reinforcement or reduction. Consequently, in this work, a novel index, *FRI*, is proposed as a sensitivity index that represents the mismatch between the current and optimum conductor sizes in each branch and can enable DSOs to determine which feeder primarily needs to be reinforced in a simple but effective manner in order to arrange their reinforcement priority plan based on the available investment capabilities. To do this, initially, a load flow analysis is required for a base system; hence *FRI* can be calculated as expressed in (6).

$$FRI = C_{loss}\left(x,y\right) - C_{inv}\left(x,y\right) \tag{6}$$

A positive value of *FRI* indicates that a feeder should be reinforced while a negative value means that the conductor size should be reduced.

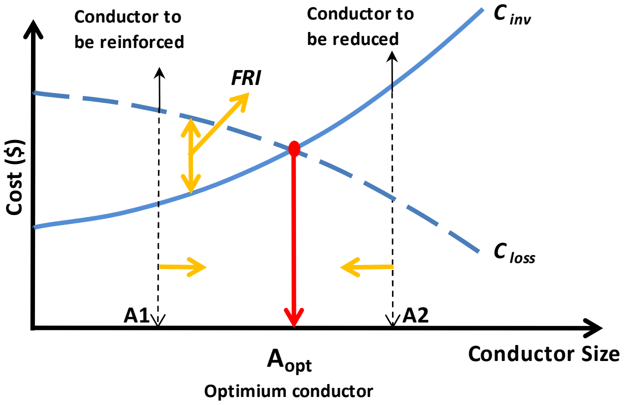


FIGURE 1. **Concept of the feeder reinforcement index.**

Feeders with large *FRI* values need to be reinforced first. However, feeders with negative *FRI* will be kept unchanged. Hence, based on *FRI* values, a feeder reinforcement approach (as an extension to the conventional approach) is proposed in this work, in which the set of optimized conductors obtained by the conventional solution is categorized into two groups: reinforced and reduced conductors. Only the reinforced conductors are considered, while the reduced conductor sizes with negative *FRI* are skipped and their original sizes are kept.

IV. OPTIMIZATION PROBLEM FORMULATION

A. OBJECTIVE FUNCTION

The objective function (OF) for the optimal selection of various types and sizes of conductors can be expressed as:

$$\text{OF} = \min\left(C_{loss,t} + C_{inv,t}\right) \tag{7}$$

where $C_{inv,t}$ is the sum of the investment costs of the conductors.

B. CONSTRAINTS

In this work, three constraints were considered. The first constraint is to ensure compliance with the system bus voltage limits, and the second is to ensure compliance with the branch thermal current limits. The third constraint is dedicated to the existing system which optimizes only the feeders that have positive *FRI*. The constraints considered are expressed as:

1) Bus voltage constraint

$$V_{min}\left(m\right) \le \left|V\left(m\right)\right| \le V_{max}\left(m\right) \qquad \forall\ \left(m \in k\right) \tag{8}$$

where $V_{min}(m)$ and $V_{max}(m)$ are minimum and maximum bus voltage values, and are considered to be 0.9 p.u. and 1.05 p.u., respectively.

2) Branch thermal capacity constraint

To avoid overheating problem, value of a branch current (I (x, y)) should be less than its thermal capacity (I_{max}), thus

$$\left|I\left(x,y\right)\right| \le I_{max}\left(y\right) \qquad \forall\ \left(x \in b, y \in n\right) \tag{9}$$

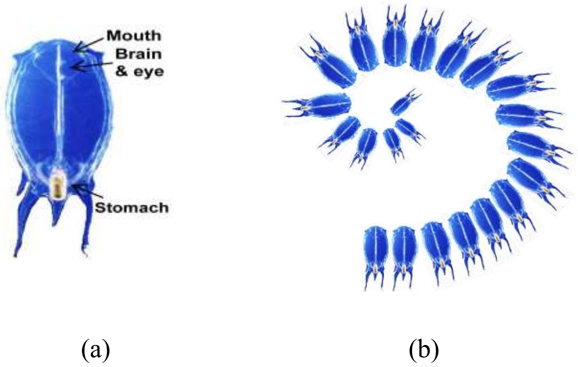
3) FRI constraint

The reinforcement action (*act*) is taken based on the *FRI* value as follows:

$$act = \begin{cases} \text{Reinforce the feeder,} & \text{if } FRI > 0 \\ \text{Keep the original size,} & \text{otherwise.} \end{cases} \tag{10}$$

C. OPTIMIZATION TECHNIQUE: SALP SWARM OPTIMIZATION (SSO) ALGORITHM

The SSO algorithm is a bio-inspired meta-heuristic optimization algorithm that was developed in 2017 based on the food-searching behavior of a salp swarm in nature [11]. Salp is a gelatinous zooplankton that has a transparent body. The salp body composition and its motion dynamics are similar to jellyfish in that water is driven through the salp's body to move via propulsion. Salps form the largest swarms on the planet (salp chain) which efficiently navigate and search for food in the deep oceans. The shape of a salp and a salp swarm are shown in Fig. 2.



(a) (b)

FIGURE 2. **(a) The shape of a salp, (b) Salp swarm (chain).**

The food-searching technique of a salp swarm is mathematically modeled as:

$$X_j^1 = \begin{cases} D_j + r_1[r_2(ub_j - lb_j) + lb_j], & \forall\ r_3 < 0.5 \\ D_j - r_1[r_2(ub_j - lb_j) + lb_j], & else \end{cases} \tag{11}$$

In the *j*th dimension, X_j^1 defines the position of the leader salp (the 1st salp). D_j is the position of the food source. *ub* and *lb* indicate the upper and lower bounds, respectively. r_1 is an adaptive coefficient in the SSO algorithm that balances between the exploration and exploitation phases, and is given as follows:

$$r_1 = 2 \times e^{-\left(\frac{4z}{Z_{\max}}\right)^2} \tag{12}$$

where z is the current iteration, and Z_{max} is the maximum number of iterations. In addition, r_2 and r_3 are random numbers in the range of [0, 1].

For the followers (salps that follow the leader salp), Newton's law of motion is used to update their positions as follows:

$$X_j^i = \frac{1}{2}at^2 + \upsilon_0 t \quad ,\text{for} \quad \forall\ i \geq 2 \tag{13}$$

where X_j^i represents the position of the *i*th follower salp at the *j*th dimension. t represents the time. v_0 indicates the initial speed which is considered to be zero. a represents the acceleration. Eq. (13) can be updated to calculate the follower salp's position as follows:

$$X_j^i = \frac{1}{2}(X_j^i + X_j^{i-1}) \tag{14}$$

One can note that SSO is a simple and easy-to-implement algorithm because it depends on only two controlling parameters, namely the number of searching salps and the maximum number of iterations. This will, in turn, facilitate improvement of the initial solutions, accelerating the convergence rate and avoiding local optima stagnation. Due to these advantages, SSO has been recently employed to solve many engineering problems [12], [13]. For more details about SSO, readers can refer to [11].

In this work, the number of search salps is set to 30 and the maximum number of iterations is set to 500. Because of the haphazardness of such heuristic-based algorithms, the reported results are obtained over 100 independent runs and are compared with different settings for the controlling parameters.

Fig. 3 shows the procedure of the proposed feeder reinforcement approach.

V. SIMULATION RESULTS AND DISCUSSION

In this section, first, the Egyptian distribution system (EDS) studied is presented. Second, various scenarios are investigated for the EDS under variable loading levels and different DG penetration levels.

A practical conductor library that includes twenty conductor types and complies with the BS-50182 [14] is used. The conductor types used and their specifications are presented in Table I. The numerical values for the parameters used in this work are k_p =1.04 ($/kW), k_e =0.06 ($/ kWh), *LSF* =0.2, *i* = 8, *F* =25 years, T=8760 hours/year, and *IDF* = 0.1.

Load flow based on a backward forward sweep technique presented in [9] and [15] is performed. This technique is used to avoid ill-conditions and ensure fast convergence. The corresponding fitness function is calculated using SSO. In order to verify the effectiveness of the proposed SSO algorithm, the EDS is examined in both Matlab and ETAP platforms. The examined system, shown in Fig. 4(a), is a typical rural (balanced and sinusoidal) system in El-Beheira Governorate in Egypt. It is supplied from a 66/11 kV transformer substation. Its base voltage and apparent power are 11 kV and 10 MVA, respectively. The substation (bus 1) is considered as the slack bus with voltage of 1 p.u. while the remaining buses are load buses (PQ buses). The line and load data for this system are given in [16]. Fig. 4(b) presents the *FRI* results for the EDS which show that the branches near the feeding substation have higher *FRI*s than the far branches that were emphasized by both the optimized and reinforced configurations.

TABLE I.
ELECTRICAL SPECIFICATIONS OF THE ACSR CONDUCTORS USED

Conductor type	*A* (mm²)	*R* (Ω/km)	*X* (Ω/km)	$I_{\max}$ (A)	*IC* ($/km)
1	6.5	2.718	0.374	70	90
2	13	1.374	0.355	120	170
3	16	1.098	0.349	130	210
4	20	0.9116	0.345	150	260
5	25	0.6795	0.339	175	340
6	30	0.5449	0.335	200	420
7	40	0.4565	0.353	250	500
8	42	0.3977	0.327	270	540
9	45	0.3841	0.327	257	590
10	48	0.3656	0.329	260	630
11	50	0.3434	0.328	270	770
12	55	0.302	0.327	290	760
13	65	0.2745	0.315	305	820
14	80	0.2193	0.282	395	1010
15	80	0.2214	0.268	380	1040
16	80	0.2221	0.271	385	1130
17	95	0.1844	0.266	425	1370
18	110	0.1589	0.261	470	1590
19	130	0.1375	0.256	510	1840
20	140	0.1223	0.252	560	2060

Three scenarios are proposed to evaluate the performance of the EDS:

i. Base scenario: the base conductors are presented according to the original system data.
ii. Optimized scenario: the conductors are set based on the conventional approach.
iii. Reinforced scenario: the conductors are set based on the proposed feeder reinforcement approach.

The scenarios are investigated under two cases: case 1: no DG unit connected and case 2: with DG unit connected. Fig. 5 summarizes the scenarios and cases studied.

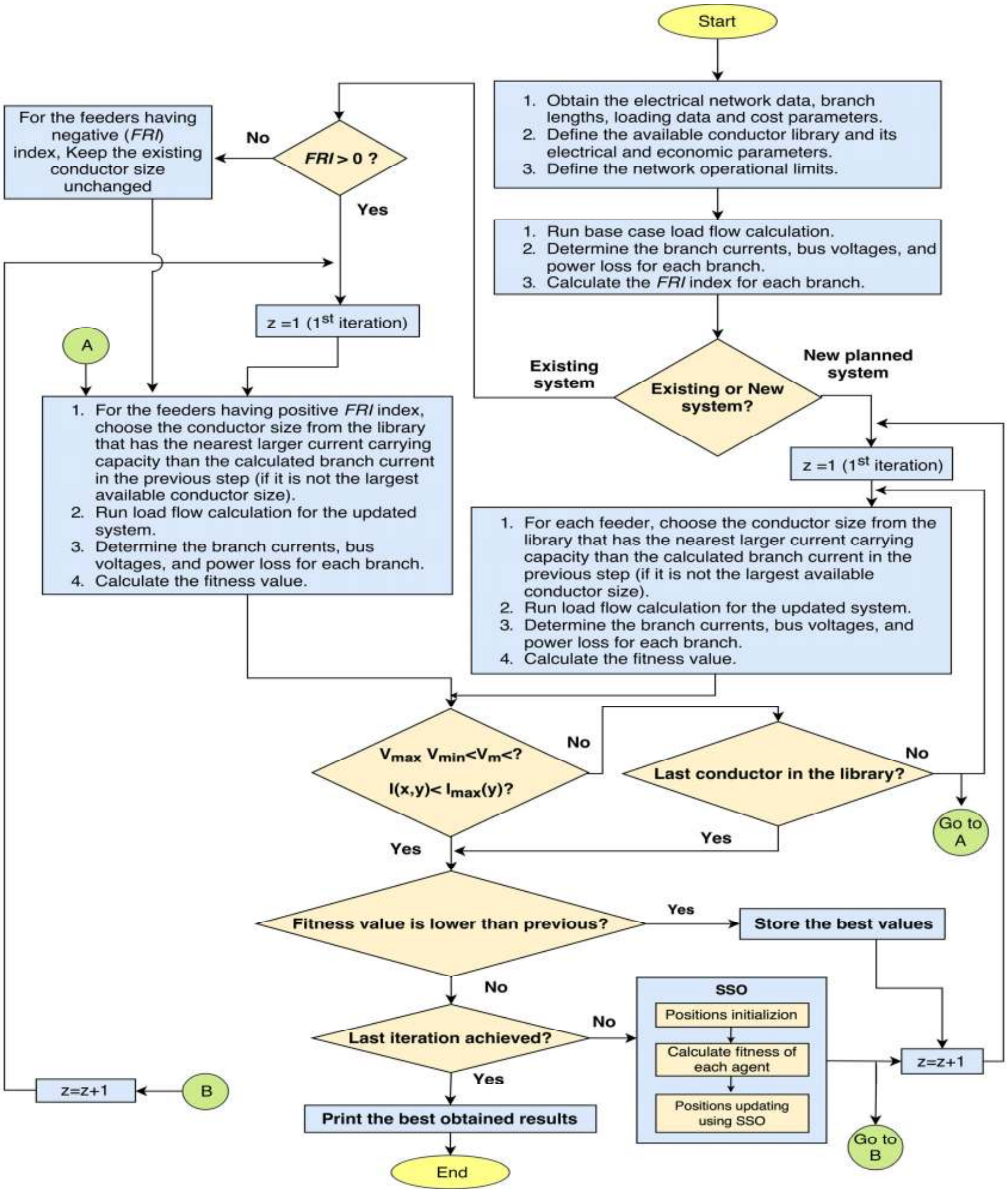
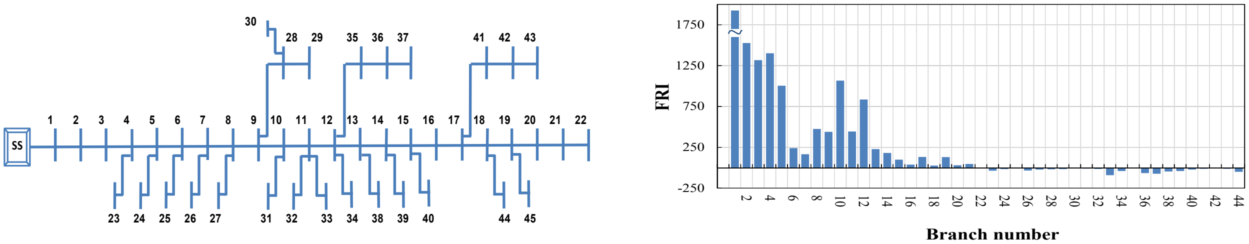


FIGURE 3. Flowchart for the proposed practical feeder reinforcement approach.



(a) (b)

FIGURE 4. EDS system: (a) Configuration of the system, (b) *FRI* results for the EDS.

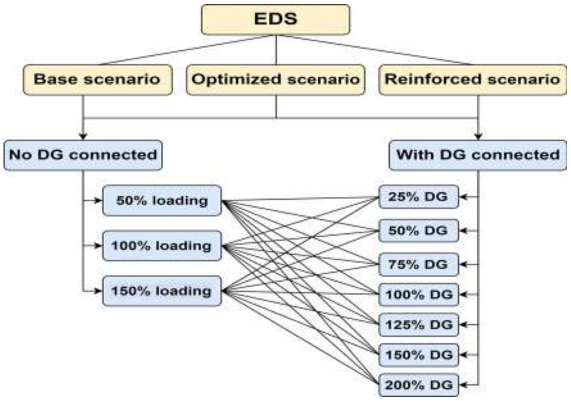


FIGURE 5. Summary of the studied scenarios and cases.

A. Case 1: No DG unit connected

The EDS is examined under different loading levels (*LLs*): 50%, 100%, and 150%. Voltage profile of the base scenario under different *LLs* is presented in Fig. 6. It is shown that various buses suffered from under voltage problems at heavy loading levels.

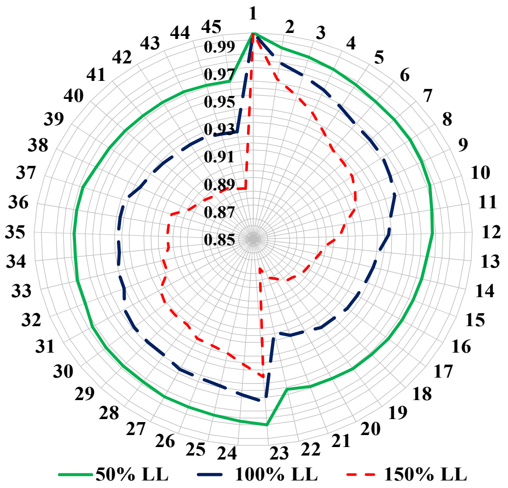


FIGURE 6. Voltage profile of the EDS system under different *LLs*

Recalling that the higher the *LL,* the lower the bus voltage values, the minimum voltage values are selected to determine the results. The minimum bus voltages at different loading levels for the scenarios examined in case 1 are given in Table II. It should be noted that the bold value in Table II indicates a violation of under voltage limit.

TABLE II.
MINIMUM BUS VOLTAGES AT DIFFERENT LOADING LEVELS FOR THE SCENARIOS EXAMINED IN CASE-1

Loading level (%)	Base	Optimized	Reinforced
50	0.9726	0.9733	0.9733
100	0.9190	0.9444	0.9444
150	**0.8717**	0.9128	0.9359

In Fig. 7, the branch current results for different scenarios are presented. For Case 1, it is seen from Fig. 7(a) and Table II that the base scenario cannot handle heavy loading levels (150%) due to violation of the current and voltage limits. However, Figs. 7(b) and 7(c) show that both the optimized and reinforced scenarios can handle all the *LLs* effectively.

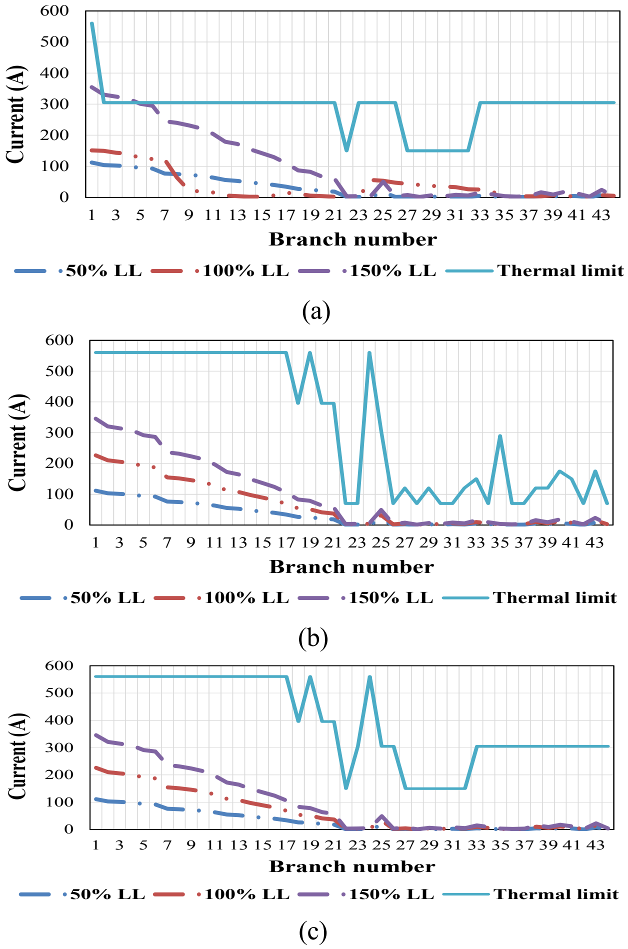


FIGURE 7. Branch currents under different *LLs* for the examined scenarios: (a) base, (b) optimized, and (c) reinforced.

In addition, it is evident that the reinforced scenario outperforms the conventionally-optimized system from the voltage, current, and power loss perspective, which will in turn give the system the ability to host more renewables as will be presented in case 2.

For the optimized scenario, Fig. 8 shows the improvement of the fitness values versus the iteration number in the SSO algorithm.

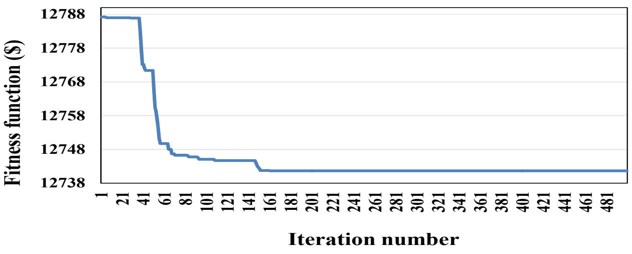


FIGURE 8. The variation of the fitness values versus number of iterations.

B. Case 2: With DG units connected

Various DG penetration levels were tested: 25%, 50%, 75%, 100, 125%, 150%, and 200%, under the same *LLs* described in the previous section. Arbitrary DG unit locations were considered at buses with the minimum voltage values of the base scenario such as buses 22 and 45.

The total system load (4.175 MW) is considered as the base value for DG penetration. DG units are considered to operate at unity power factor, i.e., injecting real active power only. The voltage profile of the three studied scenarios (base, optimized, and reinforced) examined at 100% loading and 100% DG penetration level is presented in Fig. 9 with the connected DG units. It is obvious that base scenario could not handle high DG penetration levels at the various *LLs*.

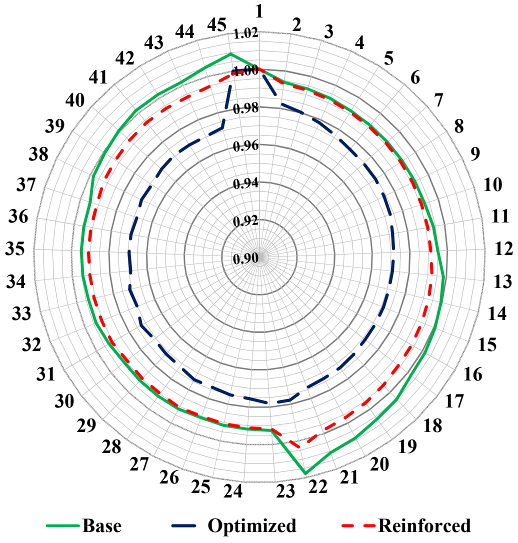


FIGURE 9. **Voltage profile of the three studied scenarios examined at 100% loading and 100% DG penetration level.**

Table III shows the cost-benefit results of the various scenarios considering different perspectives, namely power loss reduction, voltage profile enhancement, and cost of conductors. Also, Table IV presents the power loss results for the examined scenarios at the various *LLs* and DG penetration levels. From Tables III and IV, it is shown that the cost of the reinforced scenario is higher than the optimized scenario by 24%; however, the reinforced scenario succeeded in minimizing the power loss by 35% in case 1 and by 39% for 100% *LL* and 100% DG penetration level.

TABLE III.
COST-BENEFIT ANALYSIS FOR THE THREE EXAMINED SCENARIOS

Scenario	Power loss minimization	Voltage profile enhancement	Conductors cost with respect to the base system
Base	N/A	N/A	100%
Optimized	Yes (+)	Yes (+)	170%
Reinforced	Yes (++)	Yes (++)	194%

(+, ++): indicate the degrees of effectiveness of the examined analysis: (+): signifies a good improvement score, while (++) signifies the best improvement score. N/A: Not applicable.

The reinforced scenario outperforms the base and optimized scenarios from power loss reduction and voltage enhancement perspectives. Besides, the proposed reinforced approach achieved a better level of HC than can be obtained with the base and optimized scenarios at the various *LLs*.

Fig. 10 presents the results of the various configurations and the corresponding HC results obtained.

Recalling that HC depends on the performance index (PI) of interest, Figs. 10(a), 10(b), and 10(c) present a voltage-based hosting capacity (HC_V) which considers the overvoltage limit as the PI. In other words, for excessive DG penetration into distribution networks, respective bus voltage values increase; thus, the maximum bus voltage value at each *LL* is selected as a representation of the worst case result.

It is seen from Fig. 10(a) that the HC_V for the base scenario is around 100% for the 50% *LL*. Moreover, Figs. 10(b) and 10(c) show that the HC_V of the optimized and reinforced scenarios is increased and reached 112.5% and 150%, respectively. Figs. 10(c), 10(d) and 10(e) show the HC assessment while considering the thermal overload as a PI using the current difference (*DI*) that represents the difference between the thermal capacity and actual branch current. The minimum *DI* is determined for each case. When a *DI* value reaches zero, this means that the branch current is going to exceed its thermal capacity limit; accordingly, the corresponding penetration level is selected as the current-based HC result for this case (HC_I). Fig. 10(d) shows that the HC_I obtained for the base scenario has exceeded 150% for the 150% *LL*, whereas it is reduced to only 75% in the optimized scenario as shown in Fig. 10(e) because some feeder sizes have been reduced which restricted the system capability to host more DG penetration levels. On the contrary, the reinforced scenario has achieved increased HC_I results at all the loading levels tested, as shown in Fig. 10(f).

TABLE IV.
POWER LOSS RESULTS FOR THE EXAMINED SCENARIOS UNDER VARIOUS *LLS* AND DIFFERENT DG PENETRATION LEVELS

Penetration level	Base			Optimized			Reinforced		
	50% *LL*	100% *LL*	150% *LL*	50% *LL*	100% *LL*	150% *LL*	50% *LL*	100% *LL*	150% *LL*
No DG	46.90	201.23	491.31	31.50	132.21	314.00	31.22	131.00	311.03
25%	9.76	92.15	289.81	10.86	69.28	201.13	7.57	65.16	195.42
50%	19.51	40.23	161.41	24.14	44.59	132.52	11.76	31.03	116.94
75%	70.54	37.34	93.45	N/A	N/A	N/A	39.95	25.83	71.66
100%	158.91	77.60	76.92	N/A	N/A	N/A	95.98	47.39	56.47
125%	N/A	N/A	N/A	N/A	N/A	N/A	171.48	92.90	68.65
150%	N/A	N/A	N/A	N/A	N/A	N/A	271.72	163.92	107.53

N/A: Not applicable; *i.e.* HC limit has been reached.

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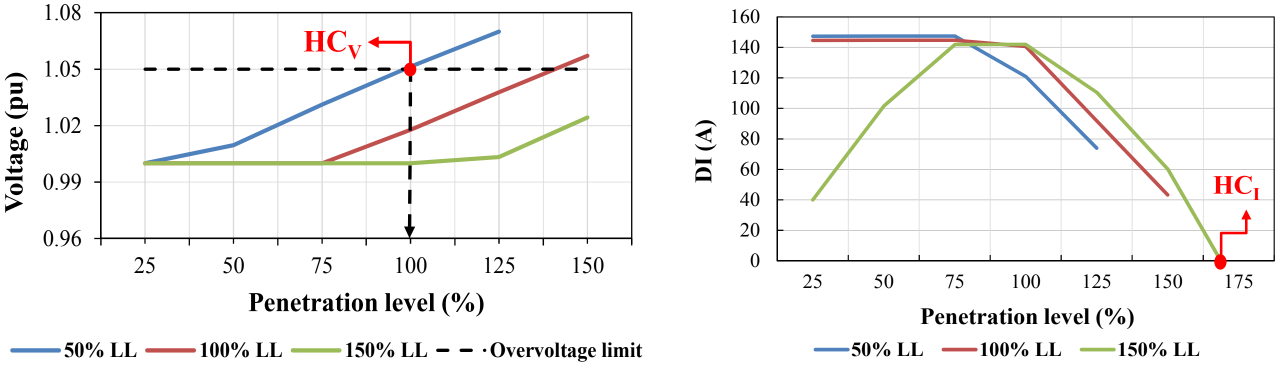
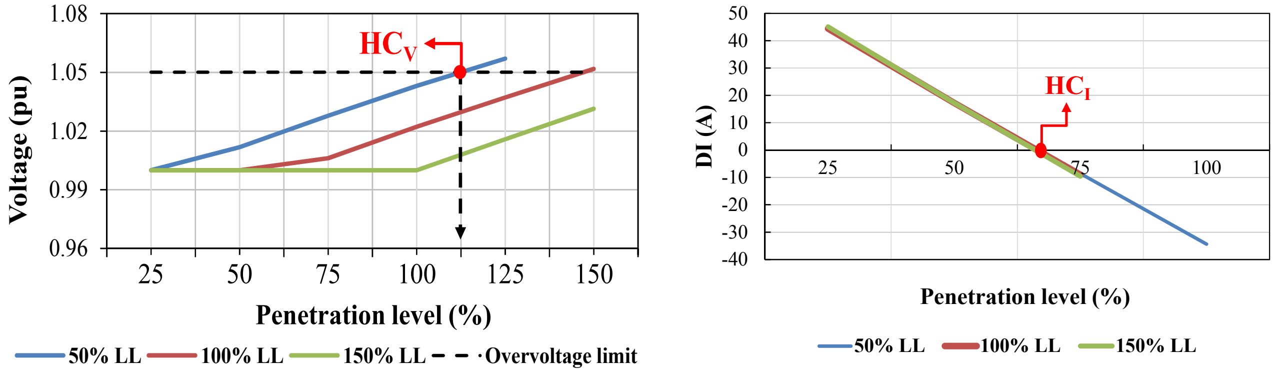


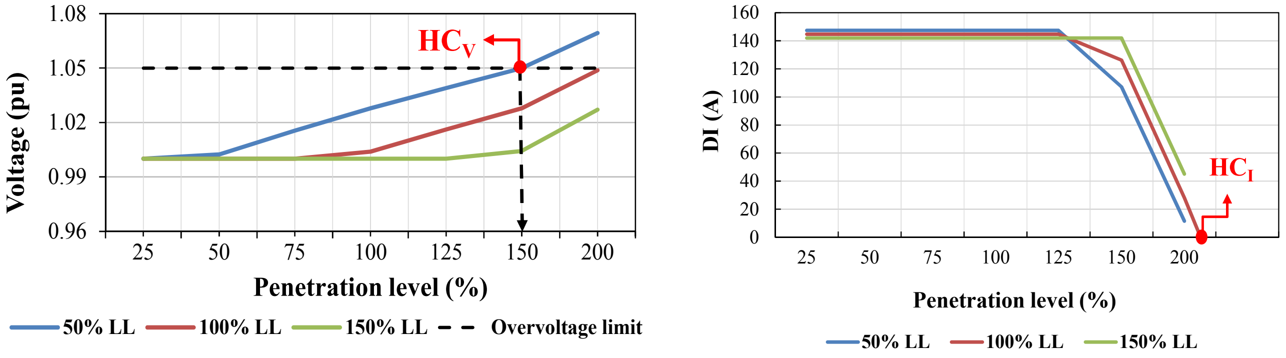
(a) Base scenario voltage-based HC

(d) Base scenario current-based HC



(b) Optimized scenario voltage-based HC

(e) Optimized scenario current-based HC



(c) Reinforced scenario voltage-based HC

(f) Reinforced scenario current-based HC

FIGURE 10. HC assessment under varying LLs, (a) Base scenario voltage-based HC, (b) optimized scenario voltage-based HC, (c) reinforced scenario voltage-based HC, (d) base scenario current-based HC, (e) optimized scenario current-based HC, and (f) reinforced scenario current-based HC.

The overall HC limits for the scenarios and cases studied are shown in Fig. 11. It should be noted that the overall HC limit for the EDS is chosen as the lowest value of the HC results that were obtained by calculations using the two PIs to ensure safe and reliable operation of the system [17]–[21].

Finally, it can be concluded that the proposed feeder reinforcement approach succeeded in attaining a better level of HC than can be obtained with the conventional conductor selection approach under the same testing conditions.

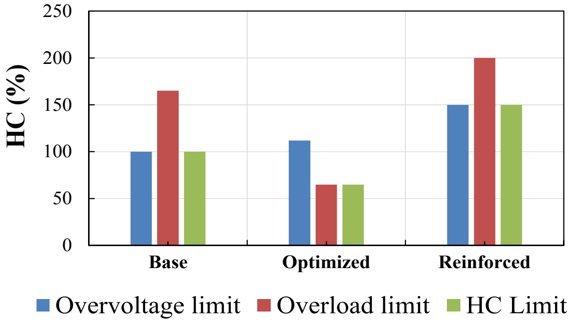


FIGURE 11. Overall HC results for the configurations studied.

VI. CONCLUSION

DG systems play a vital role in distribution power systems due to their technical, economic, social, and environmental merits. However, if not properly connected, excessive DG penetration may cause various operational problems in the distribution systems. In this paper, the optimal conductor selection problem is investigated using a recent meta-heuristic algorithm, known as SSO. A constrained optimization problem is examined to minimize the combined annual cost of energy losses and the investment cost of a real Egyptian distribution system while complying with the system voltage limits and thermal capacities of the conductors. Conventional optimal selection problem solutions may lead to a reduction of conductor sizes which is not allowed by utilities due to the practical considerations of load alteration, load growth, and the possibility of connecting DG units with uncertain penetration levels and locations. Accordingly, a novel feeder reinforcement approach is proposed to maintain the constraints while considering these uncertainties. In addition, a new *FRI* is proposed as a sensitivity index to determine the feeders that need to be reinforced first.

Based on the results achieved, it was concluded that the proposed feeder reinforcement approach succeeded in attaining a better level of HC than can be obtained with the conventional conductor selection approach under the same testing conditions in terms of various loading levels and the possibility of connecting DG units with uncertain penetration levels and locations. This will, in turn, facilitate improvement of the system reliability. Since load growth forecasts are usually considered to ensure system reliability improvement with minimal operator or customer interruptions; in this work, the proposed optimal conductor reinforcement approach was investigated for load growth considerations up to 150% in different scenarios and HC evaluation up to 150% current-based HC for thermal limit considerations and 200% voltage-based HC for voltage quality considerations. Using the HC approach to drive network reinforcements could steer DG toward areas of the network where it could have the greatest positive impact on network reliability with more win-win benefits for operators and DG owners alike.

Finally, our study was limited to the instantaneous penetration of renewables and its direct impact on the voltage quality performance of balanced systems. Another factor that was beyond the framework of this study, but will be included in future studies, is the consideration of a real-time loading profile with time-variant DG penetration in non-sinusoidal and unbalanced distribution networks, as well as considering reliability and power quality indices in a probabilistic manner to handle more DG penetration.

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