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Optimal Power Flow of Power Systems Including Distributed Generation Units Using Sunflower Optimization Algorithm

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ABSTRACT This article introduces a new attempt of utilizing the sunflower optimization (SFO) algorithm in solving the problem of optimal power flow (OPF) in the field of power systems. The principle target is to optimize the generating units' fuel cost under the system constraints. At initial stage, the objective function is solved to find the optimal siting of Distributed Generation (DG) units within the system under study. Then, different scenarios are performed to solve the OPF problem including and excluding DG units. The generators' real output power defines the exploration field for the OPF problem. The SFO algorithm is used to minimize the fitness function and yields the best solutions of the problem. More than one electric grid is tested to check the validity of the proposed algorithm such as the IEEE 14-bus, and 30-bus networks. Simulations included different scenarios are implemented in these two networks. To obtain a realistic result, real daily load curve is considered in this study. The results of simulations are investigated and analyzed. Results confirm the flexibility, validation, and applicability of the introduced SFO-based OPF methodology when compared with the genetic algorithm.

INDEX TERMS Optimal power flow, optimization, power systems, renewable energy.

I. INTRODUCTION

Power systems are considered as complex dynamic systems. They cover wide areas including many companies that are concerned with the power grids. Power grids have certain limits on the transmitted power and buses' voltages. These limits stem from temperature, voltage, and stability concerns [1]. Economic Dispatch (ED) neglects these limits. The OPF problem combines ED and power flow constraints to analyze electric power grids' performance [2]. The problem of OPF is a heavy nonlinear optimization problem, whose main target is to select the best solution of the control variables of the network or the grid, which satisfy the minimum value of the objective function taking the system constraints into consideration. Researchers can set the real output power of generators, the voltage of generators, tap-settings of the transformers, or reactive power compensation devices as control variables. The OPF objective functions, in general, may be classified into single objective functions in which, one goal is achieved, or multi-objective functions in which, many targets are reached simultaneously. These objectives can be the fuel cost of the generators, the emission rate of the generators, power losses in an electric network, and the security index of the voltage.

More than one conventional method has been proposed in the literature survey to handle the OPF problem such as Newton–Raphson (NR) [3], linear programming [4], quadratic programming [5], interior point method [6], and a semi-definite programming [7]. The previously used NR method has a drawback which is the need for a solution to a new linear system at every individual iteration [8]. Consequently, it consumes a long time to process. Acceleration can be done to avoid this disadvantage, but the convergence can be missed because of this acceleration [9]. On the other hand, quadratic programming has a disadvantage, which is the dependency on a converged AC PF. Moreover, the best solution is strongly affected by the initial guess of the problem. Due to the vicinity of assuming an

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initial solution to the problem, the AC-QP algorithm is exposed to a risk while running. It can lose the convergence [10]. Generally, traditional methods have several demerits. They are strongly affected by the initial guess of the problem which relies on the type of differential equation solver. Also, they can be stuck in a local minimum instead of a global minimum due to the nonlinearity of the OPF problem. In addition, mathematical assumptions must be defined to simplify the problem. Hereafter, it is important to find competent optimization methods to get over these disadvantages and obstacles.

Various innovative metaheuristic-based techniques were then applied to solve the OPF problem. These techniques managed to get rid of the obstacles of the mathematical conventional methods. Tabu search [11], genetic algorithm (GA) [12]–[14], particle swarm optimization (PSO) [15]–[17], biogeography-based optimization [18], [19], artificial bee colony (ABC) [20], harmony search algorithm (HSA) [21], teaching-learning based optimization [22], grey wolf optimization and differential evolution (DE) [23], shuffle frog leaping algorithm[24], gravitational search algorithm (GSA) [25], tree seed algorithm (TSA) [26], Sine-Cosine algorithm [27], and salp swarm algorithm [28] are all examples of the innovative metaheuristic-based techniques. These algorithms are inspired by nature and basically divided into swarm-based and population-based techniques. They individually have their own advantages as well as disadvantages [29]–[31]. In this regard, these optimizers are employed to reach the solution of the problem whether the goal is a single objective function or multi-objective function. These metaheuristic-based techniques initialize haphazard solutions of the agents and can reach the best solution according to their process.

A novel sunflower optimization (SFO) algorithm is used to handle the (OPF) scenarios in this study. The growth of soft computation procedures is the inspiration for using the SFO to deal with the optimization problems. The SFO algorithm is inspired from the nature behavior and it is classified as an iterative population-based metaheuristic optimization technique for multidimensional problems. Optimization using the proposed SFO algorithm is able to find a global optimal professionally [32]. Moreover, it does not get stuck in a local optimal. The advantage of the SFO algorithm is that it does not need derivatives when evaluating the objective function. The inspiration of SFO algorithm comes from sunflowers' movement to absorb the sun radiation. The cycle of a sunflower is that every morning, they rouse and follow the sun. At evening, they move in the reverse route and wait for the following morning. In this algorithm, a population of flowers is produced. They are oriented and take random steps towards the sun based on their locations. One of them will be transformed into the sun based on the assessment of each flower. For simplicity, each flower is assumed to emit one pollen gamete and it duplicates individually [33]. The simulation results made it obvious that the newly developed SFO algorithm provided better results when it was applied to solve benchmark test functions. Compared to the other optimization methods, the SFO algorithm can converge to the optimal solution efficiently in spite of the unrefined parameters. This verified its respectable performance. The algorithm obtained a healthier performance than the well-known GA and the PSO.

Due to the growth of innovative metaheuristic techniques, (OPF) problem is still active and continues with the employment of these techniques. The (OPF) problem has different objective functions. They can be solved in parallel and/or in series. The greatest well-known objective is the generators' fuel cost minimization. In this paper, the SFO is employed to handle the OPF problem. The algorithm is set to optimize a single objective function within the network limitations and restrictions. Actually, the new contributions of this study are as follows: (1) Evaluation of the effectiveness and performance of the newly published SFO algorithm in handling the OPF problems in power systems compared to the GA and the PSO, (2) Optimal siting of two Distributed Generation (DG) units using the SFO algorithm, and (3) Investigation of the effect of adding the DG units on the overall cost of fuel using the SFO, the PSO, and the GA in the OPF problem. The target is the fuel cost minimization. The introduced algorithm is used to decide the best values of the design control variables. The generators' real output power is the search space for the OPF problem. The SFO is selected to deal with the previously-mentioned problem for electric power networks such as IEEE 14- and 30-bus test systems with various scenarios. To obtain a realistic result, real daily load curve is considered in this study. Optimization results are proved using MATLAB software and the received results show a competition of the SFO with the GA and the PSO to find the OPF solution.

II. PROBLEM FORMULATION

The first objective of this study is to use the SFO algorithm to solve a classical OPF problem with the aid of MATPOWER toolbox and compare the results with the well-known GA and the PSO. The second objective is to determine the optimal location at which the DG units can be placed using the previously introduced SFO algorithm. The third objective is to run the OPF problem after inserting only the first DG unit, then, the second unit only. After that, OPF is tested while adding the both two units simultaneously. The used networks in this research are the IEEE 14-bus network and the IEEE 30-bus network. In the standard IEEE 14-bus network, generators at buses-1, 2 and 3 besides the synchronous condensers at buses-6 and 8 are the committed generators in the OPF model while in the standard IEEE 30-bus system, generators at buses-1, 2, 13, 22, 23, and 27 are the committed ones.

A. CLASSICAL OPF

The problem is a classical OPF problem and it is explained in detail in the next subsection.

1) OBJECTIVE FUNCTION

The costs purchased by the electricity suppliers are the generators running costs (mainly fuel costs) over the 24 hours of the day. The cost functions are usually represented by a quadratic function of the generator output active power as shown in (1) and (2) [34].

$$Minimize\ J = \sum_{h=1}^{24}\sum_{i=1}^{NG} C_{i,h}\left(P_{Gi,h}\right) \tag{1}$$

$$c_{i,h}\left(P_{Gi,h}\right) = a_i * P_{Gi,h}^2 + b_i * P_{Gi,h} + c_i \tag{2}$$

where: $\boldsymbol{J}$ is the total costs purchased by the electricity supplier, NG is the total number of generators, and $\boldsymbol{P_{Gi,h}}$ is the active power generated at generator bus i and hour h. The simulation is performed 96 times (every 15 minutes) for each scenario and each test system such that the step of 'h' (hour counter) is 0.25.

2) CONSTRAINTS

The constraints of the OPF problem can be written mathematically by the following Equations:

$$P_{injk,h} - \sum_{l=1}^{N} V_{k,h} * V_{l,h} * \left[G_{kl} * cos\left(\delta_{l,h} - \delta_{k,h}\right) + B_{kl} * sin\left(\delta_{l,h} - \delta_{k,h}\right)\right] = 0 \tag{3}$$

$$Q_{injk,h} - \sum_{l=1}^{N} V_{k,h} * V_{l,h} * \left[G_{kl} * sin\left(\delta_{l,h} - \delta_{k,h}\right) + B_{kl} * cos\left(\delta_{l,h} - \delta_{k,h}\right)\right] = 0 \tag{4}$$

where: $\boldsymbol{P_{injk,h}}$ is the total active power injected into the system at bus k and hour h, $\boldsymbol{Q_{injk,h}}$ is the total reactive power injected into the system at bus k and hour h, $\boldsymbol{V_{k,h}}$ and $\boldsymbol{V_{l,h}}$ are the magnitudes of the voltages at buses k and l at hour h respectively, $\mathbf{G_{kl}}$ and $\boldsymbol{B_{kl}}$ is the conductance and susceptance of the admittance $\boldsymbol{Y_{kl}}$, and $\boldsymbol{\delta_{l,h}}$ and $\boldsymbol{\delta_{k,h}}$ are the voltage angles at buses k and l at hour h respectively.

$$P_{Gmin} \leq P_{Gi,h} \leq P_{Gmax}, \quad i = 1, 2, \ldots, NG \ \ and\ h = 1, 2, \ldots, 24 \tag{5}$$

$$Q_{Gmin} \leq Q_{Gi,h} \leq Q_{Gmax}, \quad i = 1, 2, \ldots, NG \ \ and\ h = 1, 2, \ldots, 24 \tag{6}$$

$$V_{imin} \leq V_{i,h} \leq V_{imax}, \quad i = 1, 2, \ldots, NG \ \ and\ h = 1, 2, \ldots, 24 \tag{7}$$

$$V_{k,h} * V_{l,h} * \left[G_{kl} * \cos\left(\delta_{l,h} - \delta_{k,h}\right) + B_{kl} * \sin\left(\delta_{l,h} - \delta_{k,h}\right)\right] \leq P_{limkl}, \quad k, l = 1, 2, \ldots, N \tag{8}$$

where P_{limkl} is the power flow limit of the line connecting bus k and bus l.

B. OPTIMAL SITING OF THE DG UNITS

The OPF is run while trying to add the first DG unit starting from bus 2 to bus N, one at a time, where N is the number of buses of the system under study [35], [36]. The optimal selected bus at which the first unit is added is the bus which results in the minimum cost through a typical day. Similarly, the OPF is re-run to optimally allocate the second one starting from bus 2 to bus N assuming that the first unit is already installed at the previously selected bus. The previous sequence in inserting the DG units to the networks under study is named "arrangement 1". Moreover, the DG units are then inserted into the networks in a reverse sequence. DG unit '2' is inserted first, the optimal bus is obtained and then, the OPF is re-run to optimally allocate the DG unit '1' assuming that DG unit '2' is already installed at the previously selected bus. This sequence is named arrangement 2. The difference in results of optimal allocation between the two sequences of insertion of the DG units is then observed. It's assumed that the maximum capacities of the two DG units connected to the systems under study are 15 MW and 30 MW respectively.

C. OPF WITH THE DG UNITS

In reality, the renewable energy sources are intermittent and the generated power from these sources is not constant [37]. It differs according to many factors such as the season, the weather, the site [38]. For example, the output power from a wind turbine varies according to the wind speed at the site [39]. Given a wind regime, the available power output from a wind turbine can be used according to its operational characteristics [40], [41] and [42] introduce methods to handle the uncertainty issue. In this study, the uncertainty of the power generation from the DG units is neglected for simplicity and constant models of the DG units are used instead as a sample of a typical winter day. The variable output powers generated from the first and the second DG units through a typical winter day are shown in Fig. 1 and Fig. 2. The modelling data of the DG units and the power generation from them can be found in [34]. After allocating the DG units, different scenarios of the OPF problem are tested to study the effect of adding these DG units on the total costs incurred. The OPF is firstly run with adding only DG unit '1' then, OPF is run after adding only DG unit '2'. Finally, The OPF is run after adding the both DG units and the

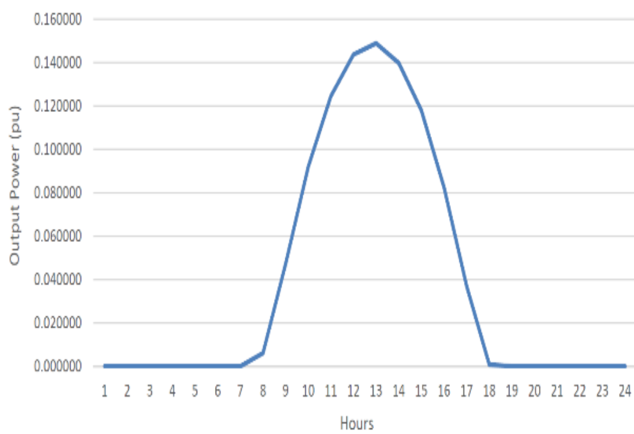

FIGURE 1. PV panel output power of a typical winter day.

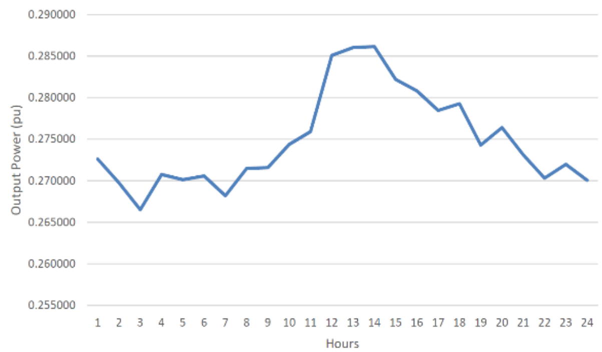

FIGURE 2. Wind turbine output power of a typical winter day.

best solution is saved for each scenario. The independent design control variable, which is the generators' active output power, is kept within its limits by the introduced SFO as presented in (5). The equality constraints are expressed in (3), (4) and (6) and they are successfully fulfilled using the full Newton-Raphson power flow with the help of MATPOWER toolbox [43] in MATLAB [44] environment. Regarding the other dependent variables, they are limited by adding penalties to the objective function which must be respected during optimizing the required objective. These penalties make the optimization process eliminate any infeasible solution. The specified penalties are explained in Eq.(9).

$$\text{Penalties} = K_v \sum_{i=1}^{N} \left[\max\left(0, V_i - V_i^{max}\right) + \max\left(0, V_i^{min} - V_i\right)\right] + K_l \sum_{j=1}^{nbr} \left[\max\left(0, S_j - S_j^{rated}\right)\right] \quad (9)$$

where K_v and K_l are very large positive numbers.

III. THE SFO ALGORITHM

The new SFO algorithm is used to handle the OPF various scenarios. The evolution of soft computation optimization algorithms is the main drive for employing the SFO algorithm to solve such optimization problems.

The inspiration of this algorithm comes from the nature. The idea of the SFO algorithm is that it simulates the sunflowers' movement to catch the sun radiation. The behavior of a sun flower is to seek the best orientation to the sun. The cycle of a sunflower is repetitive every morning. They start the day with waking up and following the sun. At the end of the day, they move in the opposite direction waiting again for the next sunrise. The inverse square law radiation is important here. As the sunflower is close to the sun, it receives much more amount of heat than the distant one and it tends to calm in this area. On the other hand, the distant sunflower gets lower amount of heat and takes greater steps to move as close as possible to the global optimum -sun- [45]. Eq.(10) describes the amount of heat received by every individual population.

$$Q_i = \frac{P}{4\pi r_i^2} \quad (10)$$

where P is the source power and r_i is the distance between the current best and population i. The pollination in this algorithm is random through the minimum distance between the flower i and the flower $i+1$. In reality, one flower patch emits enormous amount of pollen gametes. However, for simplicity of the algorithm, it is assumed that every single sunflower generates a single pollen gamete and it is solo copied. The orientation of the sunflowers towards the sun can be expressed in Eq. (11):

$$\vec{s}_i = \frac{X^* - X_i}{||X^* - X_i||}, \quad i = 1, 2, \ldots, n_p. \quad (11)$$

Eq. (12) presents the sunflowers' step towards "s":

$$d_i = \lambda \times P_i\left(X_i + X_{i-1}\right) \times ||X_i + X_{i-1}||, \quad (12)$$

where $\boldsymbol{\lambda}$ is a constant that defines an "inertial" displacement of the plants, $\boldsymbol{P_i}(||\boldsymbol{X_i}+\boldsymbol{X_{i-1}}||)$ is the pollination probability. The sunflower $\boldsymbol{i}$ pollinates with another near sunflower to produce a new one which is in an updated position. This new position differs according to the distance between the flowers. The closer individuals to the sun take fewer steps to find a local improvement. The further populations move normally. There is a restriction on these steps to prevent individuals from violating the search space which is presented in Eq. (13):

$$d_{max} = \frac{\|X_{max} - X_{min}\|}{2 \times N_{pop}} \quad (13)$$

where X_{max} and X_{min} are the maximum and minimum limits, and N_{pop} is the number of populations.

The new plantation will be:

$$\vec{X}_{i+1} = \vec{X}_i + d_i \times \vec{s}_i \quad (14)$$

Fig. 3 illustrates the steps of the introduced algorithm. Fig. 4. to Fig. 6. show some concepts about the sunflower optimization algorithm. The algorithm begins with the production of a population which may be random or even. The population with the highest evaluation among all is the one to be transformed to the sun. Then, these individuals orient themselves towards the sun and take haphazard steps towards a definite direction. This is simply the SFO algorithm.

IV. SIMULATION RESULTS

This paper introduces the solution of OPF problem handled by the SFO. The codes are written by using the MATLAB software. The standard IEEE 14-bus and 30-bus networks are used to examine the validity and success of the proposed SFO-based OPF problem. The core features of the two standard test systems are specified in Table 1.

The design control variables of the OPF problem is the real power output of generators. Simulations are performed on an Intel(R) Core (TM) i7-8550U CPU @ 1.8 GHz Processor, 8 GB RAM, 64-bit operating system, PC. The objective function is performed sequentially through the following subsections and scenarios:

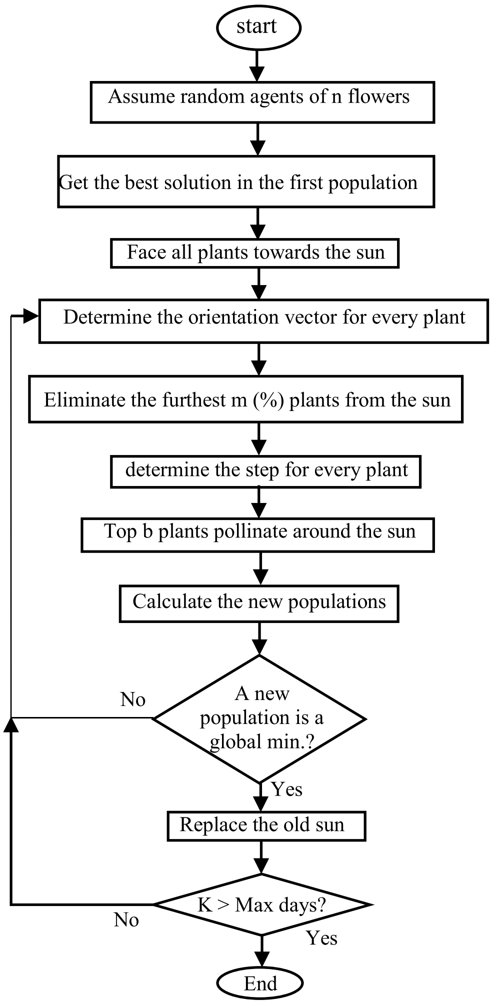

FIGURE 3. SFO Algorithm.

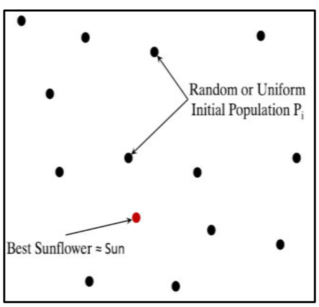

FIGURE 4. Initial population of flowers identification of the sun.

A. CLASSICAL OPTIMAL POWER FLOW PROBLEM

In this section, the study is to perform the classical OPF problem on the standard IEEE 14-bus system without adding any DG units to the network. Then the simulation is repeated for the standard IEEE 30-bus system. The limits of the design control variables of the IEEE 14-bus and 30-bus systems are expressed in [23]. Also, the fuel cost coefficients of the generating units can be found in [23]. The population size and

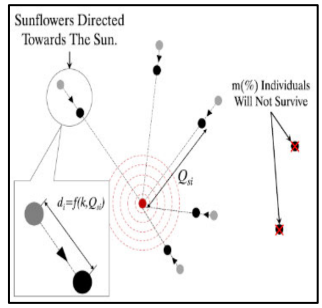

FIGURE 5. Orientation of sunflowers and towards the sun.

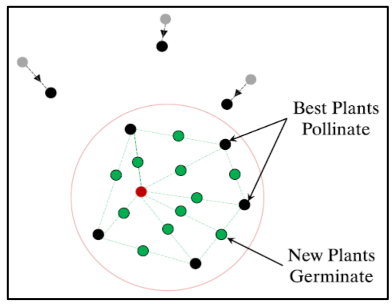

FIGURE 6. Best flowers pollinate around the sun.

TABLE 1. Main characteristics of the IEEE 14-bus and 30-bus networks.

Item	The IEEE 14-bus system [46]	The IEEE 30-bus system[46]
Number of buses	14	30
Number of generators	5	6
Number of branches	20	41
Number of transformers	3	4
Number of loads	11	21
Total connected loads	259+j81.3 MVA	283.4+j126.2 MVA

the number of iterations are adjusted to achieve a good performance of the developed SFO. The selection of SFO method controlling parameters is like any metaheuristic optimization technique. These controlling parameters are set according to the trial and error method over many independent trials and checking the algorithm performance. The stopping criteria are set as a limit for function evaluations. The studied objective function is the fuel cost. A comparison between the algorithms, the SFO, the PSO, and the GA, providing the problem constraints, number of iterations, population size and the computational time of the simulation is presented in Table 2.

Table 3 and Table 4 show the best control variables and best solutions to the objective function of the 14-bus and 30-bus systems respectively. The trials have been repeated more than once to verify the robustness of the SFO. Fig. 7 and Fig. 8 show a comparison between the convergence of the objective function using the SFO, the PSO, and GA applied on 14-bus and 30-bus systems respectively. It is seen that the objective function converged fast, smoothly

TABLE 2. Summary of simulation parameters between parameters of SFO, PSO, and GA.

	SFO		GA		PSO	
	14-bus system	30-bus system	14-bus system	30-bus system	14-bus syste m	30-bus system
No. of constraints	6912	13728	6912	13728	6912	13728
Population size	35		15		20	
No. of iterations	600					
Bus voltage penalty factor	$9x10^{15}$					
Line power flow penalty factor	$9\ x10^{13}$					
Stopping criteria (Max. no. of function evaluation)	18000		9000		600	
Computation al time (sec)	270.01	235.12	521.15	528.62	90.58	332.3

TABLE 3. Optimal control variables for the classical OPF for 14-bus system.

	SFO	GA	PSO
P_{G1} (MW)	194.6605	192.7643849	199.257
P_{G2} (MW)	36.7904	41.9911786	37.8084
P_{G3}(MW)	27.9933	21.26015334	0
P_{G4}(MW)	0.0000	7.145281	6.2716
P_{G5}(MW)	8.8547	5.375439221	89.949
Min cost($/hr)	8080.4391	8091.367821	8105.4685

TABLE 4. Optimal control variables for the classical OPF for 30-bus system.

	SFO	GA	PSO
P_{G1} (MW)	227.5525	205.8909	197.217
P_{G2} (MW)	20	27.36848	44.6833
P_{G3}(MW)	16.65896	18.9283	20.421
P_{G4}(MW)	10	14.46586	10.1543
P_{G5}(MW)	10	12.85073	10
P_{G6}(MW)	12	15.04132	12
Min cost($/hr)	906.3872	914.0514	915.7814

and stably, providing a better optimization performance to achieve the best solution with the SFO algorithm.

B. OPTIMAL SITING OF THE DG UNITS

Before performing an OPF problem with the DG units added to the system, an optimal siting is introduced with the purpose of minimizing the fuel cost with the DG units. SFO is used to optimally allocate the DG units. The simulation is done twice

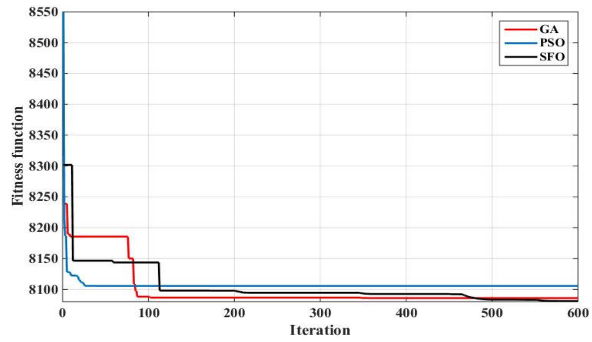

FIGURE 7. Convergence of the objective function using the SFO vs the PSO, and the GA for 14-bus system.

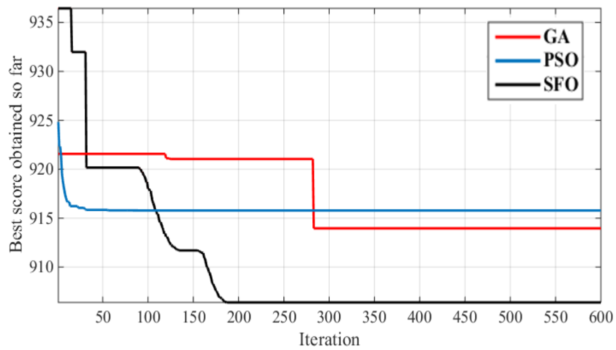

FIGURE 8. Convergence of the objective function using the SFO vs the PSO, and the GA for 30-bus system.

with different arrangement of insertion of the DG unit '1' and the DG unit '2'. The arrangement is to add the DG unit '1' first then, insert the DG unit '2' considering the existence of the DG unit '1'. The second test is to begin with optimal siting of the DG unit '2' then, insert the DG unit '1' considering the DG unit '2' is already installed. Table 5 shows the best bus at which DG unit '1' and DG unit '2' can be allocated. The simulations resulted in different optimal locations when the arrangement of inserting the DG units is reversed.

TABLE 5. Optimal buses for DG unit '1' and DG unit '2'.

Item		The IEEE 14-bus network	The IEEE 30-bus network
Best bus for DG unit '1'	Arrangement 1	5	4
	Arrangement 2	9	25
Best bus for DG unit '2'	Arrangement 1	2	21
	Arrangement 2	2	4

C. OPF WITH THE DG UNITS

In this scenario, Different cases of the OPF problem are performed. They are tested with variable load curves of the IEEE 14-bus and 30-bus systems. The load curve of the IEEE 14-bus system can be found in [34] and the load curve of the IEEE 30-bus system is extracted from [47]. Initially, the OPF problem is solved without adding any DG units.

Then, DG unit '1' is added on the previously specified buses in Table 5. Similarly, DG unit '2' is then added to the systems under study. Finally, the OPF problem is tested on a network which contains DG unit '1' and DG unit '2' together. These different cases are summarized in Table 6. Fig. 9 and Fig. 10 show the load curves for IEEE 14-bus and 30-bus Systems, respectively. The simulation of all these cases is performed using the SFO algorithm as well as GA and the PSO. The results are then compared.

TABLE 6. Cases of OPF tested in this study.

Case	Network	Bus of DG unit '1'	Bus of DG unit '2'
1	IEEE 14-bus	-	-
	IEEE 30-bus	-	-
2	IEEE 14-bus	5	-
	IEEE 30-bus	4	-
3	IEEE 14-bus	-	2
	IEEE 30-bus	-	21
4	IEEE 14-bus	5	2
	IEEE 30-bus	4	21

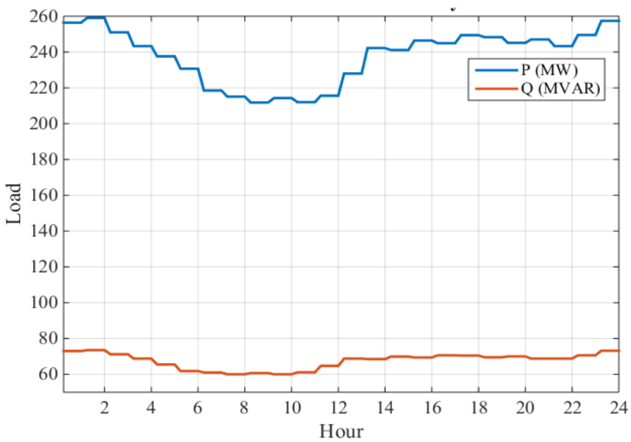

FIGURE 9. Load curves for IEEE 30-bus system.

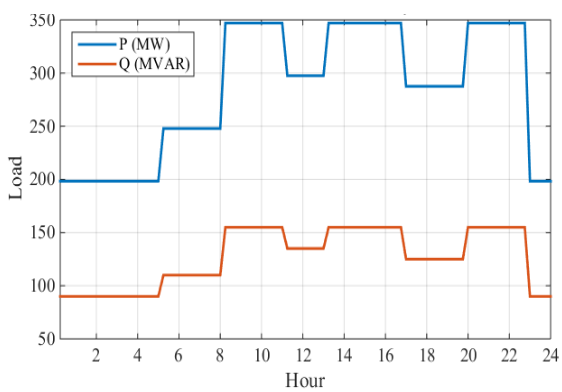

FIGURE 10. Load curves for IEEE 30-bus system.

In general, the comparison with the PSO showed that the results are very close together in the 14-bus system case but SFO shows noticeable better results in case of 30-bus system. Regarding Case 1, Fig. 11 and Fig. 12 show a fuel cost comparison using SFO, PSO, and GA which is calculated every 15 minutes. It can be noticed that the cost decreased deeply when using the SFO algorithm compared to the GA in the 14-bus system, but the results were very close to those obtained by the PSO. Meanwhile, in the 30-bus system, the reduction in cost is not the same all over the day. There is a slight reduction in cost from hours 8-11, hours 13-17, and hours 20-23 when compared to the GA. The reduction is much more noticeable during these periods when compared to the PSO.

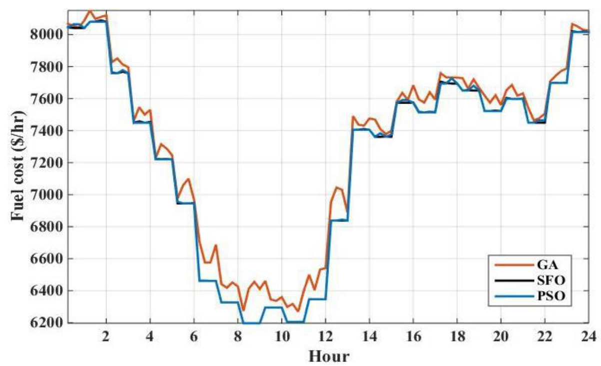

FIGURE 11. Cost comparison between SFO, PSO, and GA of case 1 for 14-bus system.

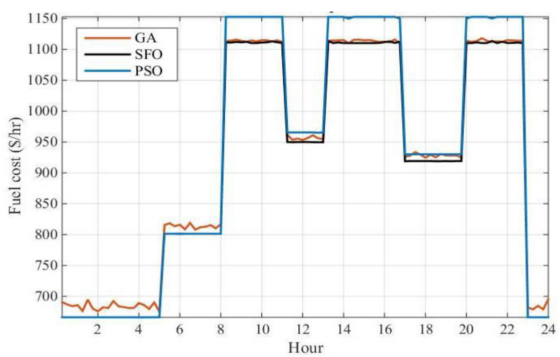

FIGURE 12. Cost comparison between SFO, PSO, and GA of case 1 for 30-bus system.

In Case 2, the IEEE 14 bus system is tested with only DG unit '1' added to bus 5, and to bus 4 in the IEEE 30 bus system. Compared to the GA, the considerable reduction in cost is between hours 6-17 in the 14-bus system. The comparison with the PSO resulted in a very close solution. In the 30-bus system, using the SFO algorithm resulted in noticeable cost reduction between hours 0-8, 11-13, 18-19, and 23-24 when compared to the GA and at the other periods of the day, the SFO is much better than the PSO as shown in Fig. 13. and Fig. 14.

Similarly, Case 3 is the case of adding only DG unit '2' to bus 2 in the IEEE 14-bus system, and to bus 21 in the IEEE 30-bus system. Fig. 15 and Fig. 16 show the fuel cost comparison. In Case 4, the IEEE 14 bus system is tested

TABLE 7. Design Control variables of IEEE 14-bus system of case 4 solved by SFO and GA.

	GA						SFO					
Hour	P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)	P_{G4} (MW)	P_{G5} (MW)	Cost($/hr)	P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)	P_{G4} (MW)	P_{G5} (MW)	Cost($/hr)
0.25	170.75	27.99	14.13	10.36	15.99	7050.046	189.32	35.62	16.03	0.00	0.00	7001.923
0.50	160.86	32.32	8.86	27.64	9.42	7084.924	188.83	36.09	8.31	4.31	3.66	7010.271
0.75	155.01	38.84	14.28	14.56	16.01	7088.531	190.59	36.08	0.53	2.41	11.95	7019.063
1.00	178.51	36.79	9.19	2.27	13.72	7025.499	189.39	35.63	16.20	0.00	0.00	7011.690
1.25	150.42	26.50	12.44	26.43	23.45	7193.871	189.57	35.67	17.02	0.00	0.00	7052.627
1.50	161.04	27.96	35.98	5.96	8.60	7127.082	190.24	33.04	13.09	0.00	5.95	7059.629
1.75	152.60	40.15	9.03	5.19	32.95	7158.497	190.41	34.44	15.64	0.00	1.98	7060.675
2.00	176.83	36.36	1.51	10.92	16.29	7092.331	189.07	34.69	6.21	5.50	7.20	7072.018
2.25	170.48	31.71	14.92	2.60	13.13	6775.420	187.90	35.35	11.22	0.00	0.00	6746.699
2.50	164.50	40.63	25.33	1.29	0.78	6782.419	187.87	35.34	11.16	0.00	0.00	6742.932
2.75	148.07	37.48	7.71	9.45	28.72	6850.222	187.84	35.34	11.08	0.00	0.00	6738.223
3.00	142.14	26.05	54.02	4.44	3.38	6905.521	187.80	35.33	11.01	0.00	0.00	6733.831
3.25	157.56	32.68	14.00	17.03	2.67	6493.177	186.08	35.00	5.15	0.00	0.00	6424.306
3.50	169.29	25.20	11.27	13.71	5.04	6486.046	186.08	35.00	5.16	0.00	0.00	6424.621
3.75	150.50	48.91	9.06	1.13	14.43	6548.584	186.09	35.00	5.18	0.00	0.00	6425.870
4.00	140.42	37.31	12.30	6.75	26.09	6565.253	186.10	35.01	5.19	0.00	0.00	6426.496
4.25	145.26	30.58	20.45	3.74	17.00	6313.603	184.85	34.77	0.90	0.00	0.00	6200.906
4.50	150.67	37.93	23.81	0.25	4.99	6276.645	185.68	34.93	0.00	0.00	0.00	6200.965
4.75	137.07	25.18	14.35	16.47	23.45	6392.605	185.67	34.93	0.00	0.00	0.00	6200.341
5.00	133.10	20.97	30.51	19.75	11.63	6443.694	184.85	34.77	0.89	0.00	0.00	6200.283
5.25	134.44	18.52	20.92	29.31	6.09	6189.111	179.37	33.69	0.00	0.00	0.00	5929.124
5.50	141.03	39.69	6.00	13.84	9.96	6059.825	179.41	33.70	0.00	0.00	0.00	5930.963
5.75	129.66	27.92	21.18	17.49	12.97	6144.533	179.46	33.71	0.00	0.00	0.00	5933.114
6.00	165.99	28.54	11.95	2.86	2.41	5970.331	179.51	33.72	0.00	0.00	0.00	5935.263
6.25	97.22	26.45	19.92	16.87	34.83	5938.674	159.80	26.07	8.15	0.00	5.01	5513.345
6.50	121.82	22.75	20.96	15.69	15.18	5742.014	168.47	31.55	0.00	0.00	0.00	5470.698
6.75	115.43	25.25	12.20	20.69	22.68	5779.825	168.42	31.54	0.00	0.00	0.00	5468.313
7.00	134.78	6.06	27.61	6.73	21.14	5839.312	168.34	31.52	0.00	0.00	0.00	5465.034
7.25	136.25	41.66	0.95	0.67	14.71	5446.349	164.98	30.87	0.00	0.00	0.00	5326.291
7.50	105.46	47.41	10.11	19.30	10.16	5686.344	164.78	30.83	0.00	0.00	0.00	5318.168
7.75	112.07	22.39	11.69	30.36	15.40	5666.272	164.62	30.80	0.00	0.00	0.00	5311.524
8.00	141.69	21.76	8.73	12.55	8.39	5441.359	164.34	30.74	0.00	0.00	0.00	5299.907
8.25	125.79	29.05	5.19	7.48	20.40	5316.728	160.31	29.96	0.00	0.00	0.00	5135.471
8.50	121.34	31.42	15.34	11.23	7.37	5297.339	159.47	29.80	0.00	0.00	0.00	5101.736
8.75	168.34	13.91	1.16	4.07	0.75	5151.736	158.48	29.61	0.00	0.00	0.00	5061.825
9.00	107.04	29.32	13.43	2.76	31.08	5337.350	157.52	29.42	0.00	0.00	0.00	5022.825
9.25	134.29	15.92	25.75	0.00	10.01	5281.453	158.79	29.68	0.00	0.00	0.00	5074.473
9.50	125.50	24.49	11.86	4.18	18.78	5225.021	157.79	29.48	0.00	0.00	0.00	5033.937
9.75	141.51	20.23	7.32	5.16	10.74	5129.545	157.10	29.35	0.00	0.00	0.00	5006.493
10.00	117.66	32.61	13.98	14.39	4.20	5173.900	156.10	29.16	0.00	0.00	0.00	4966.178
10.25	93.26	27.91	0.79	24.03	32.08	5284.114	152.74	28.51	0.00	0.00	0.00	4832.227
10.50	93.74	48.70	17.90	2.03	15.20	5231.233	152.22	28.41	0.00	0.00	0.00	4811.358
10.75	105.51	19.78	4.13	20.66	26.48	5144.848	151.20	28.21	0.00	0.00	0.00	4770.771
11.00	122.26	36.17	6.98	6.98	4.35	4872.280	150.26	28.03	0.00	0.00	0.00	4733.890
11.25	121.05	16.14	17.46	2.67	21.38	5107.634	152.88	28.54	0.00	0.00	0.00	4837.614
11.50	104.84	20.80	13.53	10.82	27.77	5189.205	152.54	28.48	0.00	0.00	0.00	4824.256
11.75	148.44	16.09	6.41	8.13	0.53	4906.843	151.95	28.36	0.00	0.00	0.00	4800.710
12.00	96.05	26.74	20.52	23.51	9.69	5191.295	151.60	28.30	0.00	0.00	0.00	4787.083

TABLE 7. ***(Continued.)*** **Design Control variables of IEEE 14-bus system of case 4 solved by SFO and GA.**

12.25	129.51	20.80	20.12	8.57	11.18	5437.174	162.61	30.44	0.00	0.00	0.00	5230.674
12.50	106.25	37.58	31.09	5.87	8.38	5539.475	162.49	30.42	0.00	0.00	0.00	5225.742
12.75	126.53	11.44	9.72	31.65	10.69	5575.786	162.41	30.40	0.00	0.00	0.00	5222.443
13.00	142.48	19.97	11.24	1.02	15.88	5351.262	162.21	30.36	0.00	0.00	0.00	5214.180
13.25	114.85	28.06	26.20	8.37	26.03	6060.688	175.27	32.92	0.00	0.00	0.00	5756.691
13.50	150.21	24.87	20.64	5.97	4.52	5877.049	175.76	33.02	0.00	0.00	0.00	5777.541
13.75	142.55	25.32	16.41	3.78	17.98	5925.266	176.05	33.07	0.00	0.00	0.00	5789.466
14.00	134.52	30.72	16.02	21.81	3.31	5972.573	176.39	33.14	0.00	0.00	0.00	5803.897
14.25	130.62	24.44	11.43	5.80	32.89	6001.979	175.84	33.03	0.00	0.00	0.00	5780.846
14.50	131.60	38.38	6.21	4.40	26.01	5985.301	176.55	33.17	0.00	0.00	0.00	5810.715
14.75	144.14	22.48	23.55	11.82	5.16	5980.780	177.03	33.26	0.00	0.00	0.00	5830.836
15.00	144.54	32.84	3.27	25.01	2.94	5971.376	177.42	33.34	0.00	0.00	0.00	5847.538
15.25	144.57	52.18	12.98	3.95	1.23	6243.571	182.90	34.42	0.00	0.00	0.00	6081.692
15.50	140.06	40.12	1.52	26.65	7.39	6280.091	183.68	34.57	0.18	0.00	0.00	6122.561
15.75	144.59	22.90	13.28	11.10	23.90	6320.443	176.22	24.51	13.63	0.00	3.66	6194.177
16.00	128.76	36.97	15.06	8.39	26.97	6396.858	184.21	34.66	1.44	0.00	0.00	6195.340
16.25	167.95	25.96	7.19	9.45	7.83	6241.301	184.25	34.67	1.16	0.00	0.00	6186.391
16.50	120.79	47.32	7.22	26.75	14.91	6515.080	184.47	34.71	1.67	0.00	0.00	6215.837
16.75	147.93	33.89	1.55	9.75	25.64	6349.776	186.58	35.12	0.00	0.00	0.00	6240.287
17.00	160.74	29.53	1.15	17.20	12.08	6356.518	184.95	34.79	2.83	0.00	0.00	6282.772
17.25	134.67	31.06	15.31	24.39	18.97	6695.239	186.26	35.04	6.98	0.00	0.00	6505.302
17.50	161.34	27.87	5.71	9.22	22.73	6611.042	186.47	35.08	7.49	0.00	0.00	6534.949
17.75	153.97	32.71	18.29	6.49	15.76	6649.264	186.75	35.13	8.15	0.00	0.00	6573.292
18.00	150.25	25.78	24.49	14.10	13.95	6769.379	188.24	34.48	7.98	1.31	0.00	6648.589
18.25	146.14	26.65	9.68	17.47	27.68	6757.126	190.98	35.95	4.44	0.00	0.00	6609.263
18.50	167.39	28.95	13.93	10.18	8.62	6654.849	187.25	36.50	5.65	0.11	1.54	6609.432
18.75	150.18	23.89	8.25	21.16	24.34	6755.544	190.97	35.94	1.89	0.81	1.77	6609.314
19.00	179.52	35.81	7.40	4.23	3.32	6612.942	187.04	35.18	8.59	0.00	0.00	6603.890
19.25	144.26	38.27	15.17	7.87	18.77	6591.059	186.31	35.04	6.16	0.00	0.00	6474.810
19.50	175.35	37.90	0.75	8.90	4.13	6499.531	186.34	35.05	6.21	0.00	0.00	6477.626
19.75	137.65	26.43	29.91	24.72	4.94	6669.431	186.36	35.05	6.26	0.00	0.00	6480.441
20.00	126.05	30.59	41.30	15.73	9.26	6722.245	186.38	35.06	6.31	0.00	0.00	6483.253
20.25	149.42	29.03	3.85	31.45	13.39	6700.054	186.82	35.14	7.79	0.00	0.00	6561.878
20.50	131.88	30.18	40.81	10.34	12.07	6764.821	186.84	35.15	7.84	0.00	0.00	6564.696
20.75	165.69	27.42	24.33	10.19	0.08	6622.510	186.85	35.15	7.88	0.00	0.00	6566.890
21.00	168.45	28.44	16.51	10.27	4.46	6614.488	186.88	35.15	7.92	0.00	0.00	6569.706
21.25	148.39	19.95	4.28	38.94	11.87	6633.923	186.09	35.00	5.17	0.00	0.00	6425.297
21.50	150.50	32.18	13.27	15.16	12.26	6520.003	186.08	35.00	5.15	0.00	0.00	6423.734
21.75	152.98	44.55	8.23	16.57	1.84	6522.581	186.07	35.00	5.12	0.00	0.00	6422.484
22.00	161.95	36.04	2.97	1.90	21.47	6471.514	185.95	35.14	5.01	0.00	0.04	6420.952
22.25	153.57	28.70	15.82	12.50	18.90	6762.370	187.53	36.07	7.69	1.20	0.00	6666.957
22.50	138.17	37.97	20.57	12.92	19.14	6819.490	187.43	35.26	9.76	0.00	0.00	6667.419
22.75	152.08	25.51	20.88	22.33	8.63	6793.282	187.45	35.26	9.79	0.00	0.00	6669.300
23.00	138.97	45.23	13.43	26.68	5.26	6850.158	187.46	35.26	9.82	0.00	0.00	6670.869
23.25	150.33	43.67	19.11	18.92	5.96	7096.621	189.24	31.59	10.01	1.44	8.17	6993.430
23.50	130.07	23.46	29.95	32.74	19.71	7256.039	189.20	35.60	15.78	0.00	0.00	6986.818
23.75	171.48	18.90	23.74	8.46	15.76	7089.839	189.20	35.60	15.78	0.00	0.00	6986.818
24.00	174.88	39.24	12.58	7.37	5.62	7008.170	190.27	33.43	7.07	2.62	7.35	6993.988

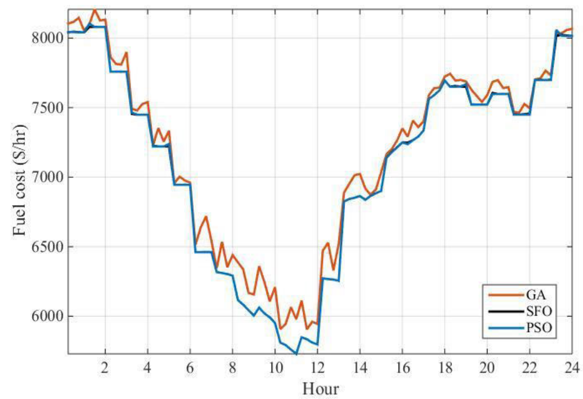

FIGURE 13. Cost comparison between SFO, PSO, and GA of case 2 for 14-bus system.

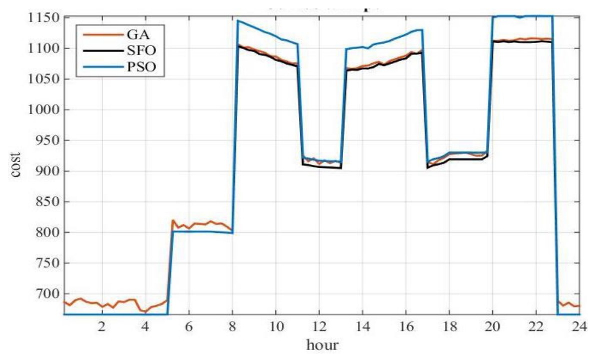

FIGURE 14. Cost comparison between SFO, PSO, and GA of case 2 for 30-bus system.

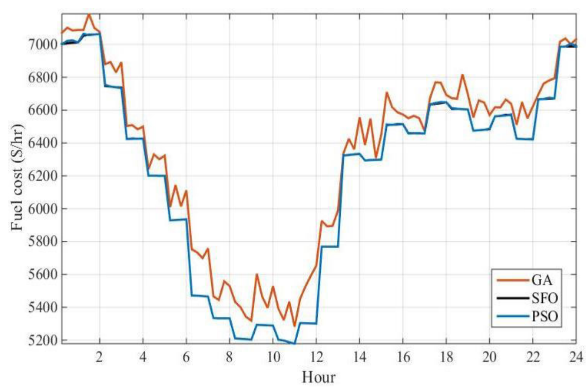

FIGURE 15. Cost comparison between SFO, PSO, and GA of case 3 for 14-bus system.

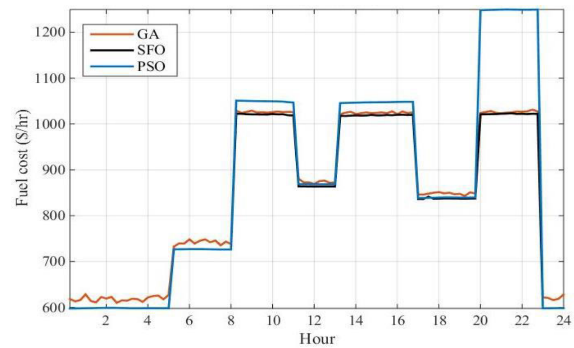

FIGURE 16. Cost comparison between SFO, PSO, and GA of case 3 for 30-bus system.

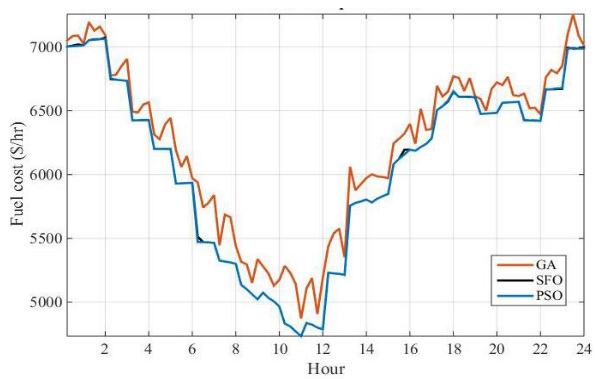

FIGURE 17. Cost comparison between SFO, PSO, and GA of case 4 for 14-bus system.

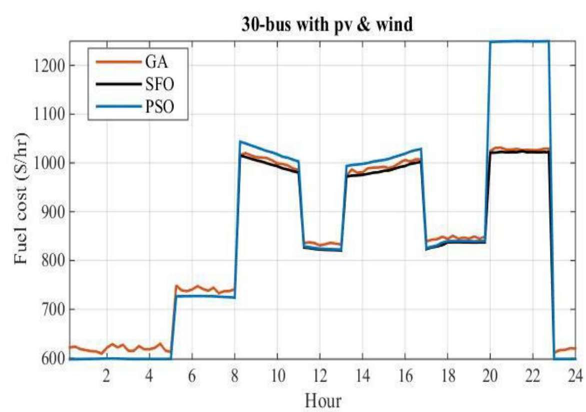

FIGURE 18. Cost comparison between SFO, PSO, and GA of case 4 for 30-bus system.

with DG unit '2' added to bus 2 and DG unit '1' added to bus 5. The IEEE 30 bus system is tested with DG unit '2' added to bus 21 and DG unit '1' added to bus 4. Fig. 17 and Fig. 18 demonstrate the fuel cost comparison and it is seen that the reduction in the fuel cost reached its maximum when both DG unit '1' and DG unit '2' are simultaneously added to the system.

Table 6 is shown as a sample for the detailed comparison of results of a typical day. It illustrates the design control variables' results when tested on the IEEE 14-bus system using the SFO, and GA under inclusion of both DG unit '2' and DG unit '1' to the system.

V. CONCLUSION

This paper has proposed a novel meta-heuristic SFO algorithm for solving the OPF problem in power systems such as the IEEE 14-bus, and 30-bus networks. Also, the SFO algorithm is used to optimally siting DG units to these systems. The OPF problem is then solved using the proposed algorithm with inclusion of these DG units. The simulation results of the OPF problem have proven the validity, accuracy, feasibility and robustness of the proposed SFO algorithm over that obtained using the other optimization methods. This superiority of the SFO comes from its high convergence speed, simple computational procedure and its proper design. Hence, when applying the SFO algorithm to solve further optimization problems, it competes the current optimization techniques and is effective in rising the quality of optimization. Finally, the proposed SFO algorithm can be used to solve many power system problems including smart grids.

REFERENCES

[1] A. J. Wood, B. F. Wollenberg, and G. B. Sheblé, *Power Generation, Operation, and Control*, 3rd ed. New York, NY, USA: Wiley, 2013.

[2] M. R. AlRashidi and M. E. El-Hawary, "Hybrid particle swarm optimization approach for solving the discrete OPF problem considering the valve loading effects," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 2030–2038, Nov. 2007.

[3] G. Radman and J. Shultz, "A new derivation for Newton-based optimal power flow solution," *Electr. Power Compon. Syst.*, vol. 33, no. 6, pp. 673–684, 2005.

[4] R. Mota-Palomino and V. H. Quintana, "Sparse reactive power scheduling by a penalty function - linear programming technique," *IEEE Trans. Power Syst.*, vol. PWRS-1, no. 3, pp. 31–39, Aug. 1986.

[5] N. Grudinin, "Reactive power optimization using successive quadratic programming method," *IEEE Trans. Power Syst.*, vol. 13, no. 4, pp. 1219–1225, Nov. 1998.

[6] A. A. Sousa, G. L. Torres, and C. A. Canizares, "Robust optimal power flow solution using trust region and interior-point methods," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 487–499, May 2011.

[7] B. Xiaoqing and H. Wei, "A semidefinite programming method with graph partitioning technique for optimal power flow problems," *Int. J. Elect. Power Energy Syst.*, vol. 33, no. 7, pp. 1309–1314, 2011.

[8] A. K. Laha, K. E. Bollinger, R. Billinton, and S. B. Dhar, "Modified form of Newton's method for faster load-flow solutions," *Proc. Inst. Elect. Eng.*, vol. 121, no. 8, pp. 849–853, Aug. 1974.

[9] J. Lobry, J. Trecat, and C. Broche, "The transmission line modeling (TLM) method as a new iterative technique in nonlinear 2-D magnetostatics," *IEEE Trans. Magn.*, vol. 32, no. 2, pp. 559–566, Mar. 1996.

[10] J. F. Marley, D. K. Molzahn, and I. A. Hiskens, "Solving multiperiod OPF problems using an AC-QP algorithm initialized with an SOCP relaxation," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3538–3548, Sep. 2017.

[11] M. A. Abido, "Optimal power flow using tabu search algorithm," *Electr. Power Compon. Syst.*, vol. 30, no. 5, pp. 469–483, 2010.

[12] M. S. Kumari and S. Maheswarapu, "Enhanced genetic algorithm based computation technique for multi-objective optimal power flow solution," *Int. J. Elect. Power Energy Syst.*, vol. 32, no. 6, pp. 736–742, 2010.

[13] A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis, "Optimal power flow by enhanced genetic algorithm," *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 229–236, May 2002.

[14] A.-F. Attia, Y. A. Al-Turki, and A. M. Abusorrah, "Optimal power flow using adapted genetic algorithm with adjusting population size," *Electr. Power Compon. Syst.*, vol. 40, no. 11, pp. 1285–1299, 2012.

[15] R.-H. Liang, S.-R. Tsai, Y.-T. Chen, and W.-T. Tseng, "Optimal power flow by a fuzzy based hybrid particle swarm optimization approach," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1466–1474, 2011.

[16] H. M. Hasanien, "Particle swarm design optimization of transverse flux linear motor for weight reduction and improvement of thrust force," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4048–4056, Sep. 2011.

[17] V. H. Hinojosa and R. Araya, "Modeling a mixed-integer-binary small-population evolutionary particle swarm algorithm for solving the optimal power flow problem in electric power systems," *Appl. Soft Comput.*, vol. 13, no. 9, pp. 3839–3852, 2013.

[18] A. Bhattacharya and P. K. Chattopadhyay, "Application of biogeography-based optimisation to solve different optimal power flow problems," *IET Gener., Transmiss. Distrib.*, vol. 5, no. 1, pp. 70–80, Jan. 2011.

[19] J. Cao, F. Wang, and P. Li, "An improved biogeography-based optimization algorithm for optimal reactive power flow," *Int. J. Control Automat.*, vol. 7, no. 3, pp. 161–176, 2014.

[20] A. Khorsandi, S. H. Hosseinian, and A. Ghazanfari, "Modified artificial bee colony algorithm based on fuzzy multi-objective technique for optimal power flow problem," *Electr. Power Syst. Res.*, vol. 95, no. 2, pp. 206–213, 2013.

[21] S. Sivasubramani and K. S. Swarup, "Multi-objective harmony search algorithm for optimal power flow problem," *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 3, pp. 745–752, 2011.

[22] M. Ghasemi, S. Ghavidel, M. Gitizadeh, and E. Akbari, "An improved teaching–learning-based optimization algorithm using Lévy mutation strategy for non-smooth optimal power flow," *Int. J. Electr. Power Energy Syst.*, vol. 65, pp. 375–384, 2015.

[23] A. A. El-Fergany and H. M. Hasanien, "Single and multi-objective optimal power flow using grey wolf optimizer and differential evolution algorithms," *Electr. Power Compon. Syst.*, vol. 43, no. 13, pp. 1548–1559, 2015.

[24] T. Niknam, M. R. Narimani, M. Jabbari, and A. R. Malekpour, "A modified shuffle frog leaping algorithm for multi-objective optimal power flow," *Energy*, vol. 36, no. 11, pp. 6420–6432, 2011.

[25] S. Duman, U. Guvenc, Y. Sonmez, and N. Yorukeren, "Optimal power flow using gravitational search algorithm," *Energy Convers. Manage.*, vol. 59, no. 7, pp. 86–95, 2012.

[26] A. A. El-Fergany and H. M. Hasanien, "Tree-seed algorithm for solving optimal power flow problem in large-scale power systems incorporating validations and comparisons," *Appl. Soft Comput. J.*, vol. 64, pp. 307–316, Mar. 2017.

[27] A. F. Attia, R. A. El Sehiemy, and H. M. Hasanien, "Optimal power flow solution in power systems using a novel sine-cosine algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 99, pp. 331–343, Jun. 2018.

[28] A. A. El-Fergany and M. H. Hasanien, "Salp swarm optimizer to solve optimal power flow comprising voltage stability analysis," *Neural Comput. Appl.*, pp. 1–17, Jan. 2019.

[29] S. S. Reddy and P. R. Bijwe, "Efficiency improvements in meta-heuristic algorithms to solve the optimal power flow problem," *Int. J. Elect. Power Energy Syst.*, vol. 82, pp. 288–302, Nov. 2016.

[30] A. M. Shaheen, S. M. Farrag, and R. A. El-Sehiemy, "MOPF solution methodology," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 2, pp. 570–581, 2016.

[31] A. E. Chaib, H. R. E. H. Bouchekara, R. Mehasni, and M. A. Abido, "Optimal power flow with emission and non-smooth cost functions using backtracking search optimization algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 81, pp. 64–77, Oct. 2016.

[32] M. H. Qais, H. M. Hasanien, and S. Alghuwainem, "Identification of electrical parameters for three-diode photovoltaic model using analytical and sunflower optimization algorithm," *Appl. Energy*, vol. 250, pp. 109–117, Sep. 2019.

[33] G. F. Gomes, S. S. da Cunha, and A. C. Ancelotti, "A sunflower optimization (SFO) algorithm applied to damage identification on laminated composite plates," *Eng. Comput.*, vol. 35, no. 2, pp. 619–626, 2018.

[34] H. R. G. Ibrahim, "Impact of demand response and battery energy storage system on electricity markets," Ph.D. dissertation, Elect. Comput. Eng., Univ. Waterloo, Waterloo, Ontario, Canada, 2017.

[35] G. Islam, S. M. Muyeen, A. Al-Durra, and H. M. Hasanien, "RTDS implementation of an improved sliding mode based inverter controller for PV system," *ISA Trans.*, vol. 62, pp. 50–59, May 2016.

[36] R. N. Kalaam, S. M. Muyeen, A. Al-Durra, H. M. Hasanien, and K. Al-Wahedi, "Optimisation of controller parameters for grid-tied photovoltaic system at faulty network using artificial neural network-based cuckoo search algorithm," *IET Renew. Power Gener.*, vol. 11, no. 12, pp. 1517–1526, Oct. 2017.

[37] M. H. Qais, H. M. Hasanien, and S. Alghuwainem, "Enhanced salp swarm algorithm: Application to variable speed wind generators," *Eng. Appl. Artif. Intell.*, vol. 80, pp. 82–96, Apr. 2019.

[38] M. A. Soliman, H. M. Hasanien, H. Z. Azazi, E. E. El-Kholy, and S. A. Mahmoud, "An adaptive fuzzy logic control strategy for performance enhancement of a grid-connected PMSG-based wind turbine," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3163–3173, Jun. 2019.

[39] F. Islam, M. Hany Hasanien, A. Al-Durra, and S. M. Muyeen, "A new control strategy for smoothing of wind farm output using short-term ahead wind speed prediction and flywheel energy storage system," in *Proc. Amer. Control Conf. (ACC)*, Montreal, QC, Canada, Jun. 2012, pp. 27–29.

[40] B. Zeng, X. Wei, D. Zhao, C. Singh, and J. Zhang, "Hybrid probabilistic-possibilistic approach for capacity credit evaluation of demand response considering both exogenous and endogenous uncertainties," *Appl. Energy*, vol. 229, pp. 186–200, Nov. 2018.

[41] G. Sadikoglu, "Modeling of consumer buying behaviour using Z-number concept," *Intell. Automat. Soft Comput.*, vol. 24, no. 1, pp. 173–178, 2018.
[42] A. T. Saric and A. M. Stankovic, "An application of interval analysis and optimization to electric energy markets," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 515–523, May 2006.
[43] MATPOWER. *The Newton-Raphson Method*. [Online]. Available: http://www.pserc.cornell.edu/matpower
[44] *MATLAB*, MathWorks, Natick, MA, USA, 2014.
[45] C. R. McInnes, "Solar radiation pressure," in *Solar Sailing* (Astronomy and Planetary Sciences). London, U.K.: Springer, 1999.
[46] *A Data Sheet for IEEE 14 Bus System*. Accessed: Sep. 8, 2018. [Online]. Available: www.academia.edu/7781632/a_data_sheets_for_ieee_14_bus_system
[47] M. Amroune, A. Bourzami, and T. Bouktir, "Weakest buses identification and ranking in large power transmission network by optimal location of reactive power supports," *Indonesian J. Electr. Eng.*, vol. 12, no. 10, pp. 7123–7130, Oct. 2014.

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