Application of Sunflower Optimization Algorithm for Solving the Security Constrained Optimal Power Flow Problem

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Abstract—**Finding the Optimal Power Flow (OPF) which minimizes total generator cost is the answer to one of the most important problems in the electricity market operation. Independent System Operators (ISO) face many challenges while operating the system in order to obtain economic benefits and security. The solution to this problem is known as Security Constrained Optimal Power Flow (SCOPF). SCOPF is a very large-scale and nonlinear optimization problem with many complex constraints. This paper proposes the Sunflower Optimization (SFO) algorithm for solving the SCOPF problem. The proposed method is tested on the IEEE 30-bus and the IEEE 118-bus systems for both normal and outage cases. The result comparison with other known methods showed that the proposed SFO algorithm is an effective method for solving the SCOPF problem in the electricity market.**

Keywords-OPF; SCOPF; SFO, electricity market

I. INTRODUCTION

The restructuring of the electricity industry made the electrical energy a commodity. However the Independent System Operators (ISO) are facing many challenges in terms of system operation to obtain economic benefits and security. Various factors such as the expansion of the generation and transmission systems have not been in accordance with the increase in demand. Besides, the number of unplanned power exchanges increases and direct contracts between producers and consumers sometimes cause insecure operation of the system. Hence, power system security [1] has become one of the most important aspects in the electricity market operation [2]. This problem is known as the Security Constrained Optimal Power Flow (SCOPF) [3-5] which is an extension of the OPF problem [6] which is used to obtain an economical operation of the system while considering not only normal operating limits, but also violations that would occur during contingencies. The SCOPF changes the system's pre-contingency operating point so that the total operating cost is minimized, and at the same time no security limit is violated if contingencies occur. Although the SCOPF still faces challenges related to computations, it is expected that it eventually become a standard tool in the electricity market [7]. Various mathematical programming solutions have been proposed to solve the SCOPF problem such as iterative approach [8], Benders decomposition approach [9], linear programming [10], quadratic programming [11], and interior point method [12]. Recently, many Artificial Intelligence algorithms have been proposed for solving optimization problems in power system [13-18]. Among them several approaches were used to deal with the SCOPF problem such as Particle Swarm Optimization (PSO) [16], Genetic Algorithm (GA) [17], and Evolutionary Programming (EP) [18]. In [19], a PSO approach was presented to solve an Optimal Power Flow (OPF) problem with embedded security constraints represented by a mixture of continuous and discrete control variables, where the major aim is to minimize the total operating cost, taking into account both operating security constraints and system capacity requirements. A new robust differential evolution algorithm for SCOPF, considering detailed generator model is presented in [20], in which a hybrid constraint handling method has been proposed to enhance the diversity of the search process and increases the chance of finding the optimum solution. In [21], the authors presented a Self-Organizing Hierarchical PSO with Time-Varying Acceleration Coefficients (SOHPSO-TVAC) for dealing with the SCOPF problem, which was designed to avoid premature convergence. The SCOPF problem has been solved in [22] with the use of Adaptive Flower Pollination Algorithm (APFPA), where the control variables are optimized based on an adaptive and flexible structure which allows creating diversity and balance between exploration and exploitation during the search process.

In this paper, the Sunflower Optimization (SFO) algorithm [23] is proposed for solving the SCOPF problem. SFO algorithm is inspired by nature and is classified as an iterative, population-based, meta-heuristic optimization technique for multidimensional problems. The sunflowers operate in a cycle. In the morning they stir and follow the sun throughout the day. At evening, they move in the opposite direction and wait until the next morning. A population of flowers is created in a direction and takes random steps towards the sun based on their position. The proposed SFO algorithm is able to find a global optimal solution, without stucking in local optimal solutions. The advantage of the SFO algorithm is that it does not need

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derivatives when evaluating the objective function [24]. The proposed method is tested on the IEEE 30-bus and the IEEE 118-bus systems, and the results are compared with the results of other known methods.

II. OBJECTIVE FUNCTION

The SCOPF problem is a very large-scale and nonlinear optimization problem with many complex constraints. The SCOPF problem consists of optimizing the total generator fuel-cost function, subject to power-balance and inequality constraints of the base-case state and the contingency-case states [3]. Mathematically, the SCOPF problem can be formulated as follows:

$$\mathrm{Min}\, f(x, u) \quad (1)$$

subject to the equality and inequality constraints of the normal case (2)-(3) and the outage case (4)-(5):

$$g(x, u) = 0 \quad (2)$$

$$h(x, u) \le 0 \quad (3)$$

$$g(x^c, u^c) = 0 \quad (4)$$

$$h(x^c, u^c) \le 0 \quad (5)$$

where F is the fuel cost function of the generator, x is the vector of control variables, u is the vector of state variables, $g(.)$ is the set of equality constraints, $h(.)$ is the set of the inequality constraints, and c is the set of outage lines.

The detailed model of the problem is formulated as follows:

$$\mathrm{Min}\, f = \sum_{i=1}^{N_g} f_i(P_{Gi}) \quad (6)$$

where $f_i(P_{Gi})$ is the fuel cost function of generator i :

$$f_i(P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (7)$$

where P_{Gi} is the power output of generator i and a_i, b_i, c_i, are cost coefficients.

The equality and inequality constraints for the normal and outage cases are:

- Power balance constraints:

$$P_{Gi} - P_{Di} = |V_i| \sum_{j=1}^{N_b} |Y_{ij}||V_j| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (8)$$

$$Q_{Gi} - Q_{Di} = |V_i| \sum_{j=1}^{N_b} |Y_{ij}||V_j| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (9)$$

where Q_{Gi} is the reactive power output of generator i, P_{Di} and Q_{Di} are the active and reactive power demands at bus i respectively, i=1, 2,…, N_b, N_b is the number of buses in the system, $|V_i|\angle\delta_i$ and $|V_j|\angle\delta_j$ are the voltage at buses i and j, respectively, and $|Y_{ij}|\angle\theta_{ij}$ is an element in Y_{bus} matrix related to buses i and j.

- Power generation limits:

$$P_{Gi,min} \le P_{Gi} \le P_{Gi,max} \quad (10)$$

$$Q_{Gi,min} \le Q_{Gi} \le Q_{Gi,max} \quad (11)$$

where $P_{Gi,max}$ is the maximum active power output of generator i, $Q_{Gi,min}$ and $Q_{Gi,max}$ are the minimum and maximum reactive power outputs of generator i, i=1, 2, …, N_G, and N_G is the number of generators.

- Bus voltage limits:

$$V_{Gi,min} \le V_{Gi} \le V_{Gi,max},\ i = 1, 2, \ldots, N_G \quad (12)$$

$$V_{li,min} \le V_{li} \le V_{li,max},\ i = 1, 2, \ldots, N_d \quad (13)$$

- Transmission line limits:

$$S_l \le S_{l,\max},\ l = 1, 2, \ldots, N_l \quad (14)$$

V_{Gi} is the voltage at generation bus i, V_{li} is the voltage at load bus i, $V_{Gi,max}$ and $V_{Gi,min}$ are the maximum and minimum voltages at generation bus i respectively, $V_{li,max}$ and $V_{li,min}$ are the maximum and minimum voltages at load bus i respectively, and N_d is the number of load buses.

III. APPLICATION OF THE SFO ALGORITHM

The flowchart of the process of applying the SFO for solving the SCOPF problem is shown in Figure 1. Its steps are presented below.

Step 1: Read the power system data and select control parameters such as mortality rate m, population size n, pollination rate p, and maximum iteration number $max_{i.tr}$

Step 2: Initialize a population of n individuals: Each individual contains a vector of control variables represented by:

$$\begin{gathered} X_i = [P_{G2}, P_{G3}, \ldots, P_{GN_G}, V_{G1}, V_{G2}, \ldots, V_{GN_G}, Q_{c1}, Q_{c2}, \ldots, Q_N] \\ i = 1, \ldots, n \end{gathered} \quad (15)$$

Each individual in the population is initialized by:

$$X_i^{(0)} = X_i^{\min} + rand_1 * (X_i^{\max} - X_i^{\min}) \quad (16)$$

where X_i^{max} and X_i^{min} are the upper and lower limits of each individual and $rand_1$ is a random numbers in the range [0,1].

Step 3: Evaluation of the initialized population: The power flow problem is solved for the initialized population and the obtained result is used to evaluate the quality of the initialized population via calculating the fitness function including the outage case:

$$\begin{aligned} F_f &= \sum_{i=1}^{N_G} f_i(P_{Gi}) + K_{p0} * (P_{G1} - P_{G1}^{\lim})^2 \\ &+ K_{q0} * \sum_{i=1}^{N_g} (Q_{Gi} - Q_{Gi}^{\lim})^2 + K_{v0} * \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim})^2 \\ &+ K_{s0} * \sum_{l=1}^{N_l} (S_l - S_{l,\max})^2 \\ &+ \sum_{c=1}^{N_c} \left(\begin{aligned} & K_p * (P_{G1} - P_{G1}^{\lim,c}) + K_q * \sum_{i=1}^{N_g} (Q_{Gi} - Q_{Gi}^{\lim,c})^2 \\ & + K_v * \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim,c})^2 + K_s * \sum_{l=1}^{N_l} (S_l - S_{l,\max,c})^2 \end{aligned} \right) \end{aligned} \quad (17)$$

Step 4: Individuals adjustment: Each individual (sunflower) adjust its position towards the best solution (sun) as shown in (18):

$$\vec{s}_i = \frac{X^* - X_i}{\left\| X^* - X_i \right\|}, \quad i = 1,2....,n \qquad (18)$$

where X^* is the overall best solution with the corresponding best fitness function F_f in the population, and X_i is the current solution. The furthest individuals are eliminated.

Step 5: Solve the power flow problem for each individual after adjusting its position and update the best fitness value.

Step 6: Individuals movements and update: The step of each individual towards the best individual is calculated in (19) and the individuals update their positions as shown in (20).

$$d_i = \lambda \times P_i\left(\left\| X_i + X_{i-1} \right\|\right) \times \left\| X_i + X_{i-1} \right\| \qquad (19)$$

$$\vec{X}_{i+1} = X_i + d_i \times \vec{s}_i \qquad (20)$$

Step 7: Evaluate the new individuals: The power flow problem is solved for the new population $X_i^{(n)}$ and the obtained result is used to calculate the fitness function $F_f^{(n)}$ in (17).

Step 8: Accept the new individuals if their fitness function value is better than the current values.

Step 9: Check the stopping criteria. If $n < N_{max}$, $n = n + 1$ then return to Step 4, otherwise, stop.

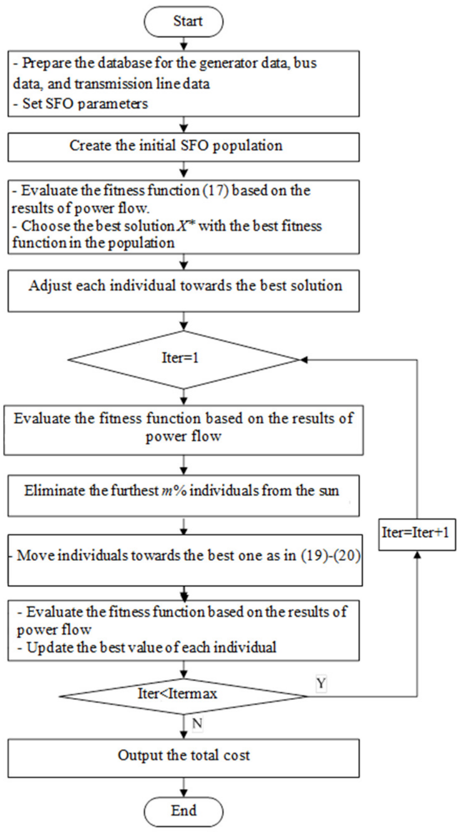

Fig. 1. The flowchart of the proposed process

IV. RESULTS

The proposed SFO algorithm has been tested on the IEEE 30-bus and the IEEE 118-bus systems for both normal and outage cases. The IEEE 30-bus test system is composed of 6 generators at buses 1, 2, 5, 8, 11, and 13, four transformers and 41 transmission lines as shown in Figure 2. The total system demand was 283.4MW and 126.6Mvar. The bus and branch data with the fuel cost coefficients are given in [4, 31]. For the outage cases, the 5-outage lines 1, 2, 3, 5, and 7 are considered. The IEEE 118-bus system consists of 118 buses, 186 branches, 99 load sides, 54 thermal units, and 9 transformers. In the outage cases, outages of lines 21 and 50 were considered. The data of the system are derived from [25, 32]. For the implementation of the proposed method, the control parameters of the proposed SFO for the test system are selected experimentally as follows. The population number n is set to 15, the mortality rate m to 0.1, the pollination rate p to 0.05, and all penalty factors to 10^6. The number of iterations is set to 300 for the normal case, and 400 for the case with 5 outage lines. The proposed SFO method was coded in Matlab 2014a and Matpower platform, and ran in a Microsoft Windows 7 PC with Intel(R) Core(TM)2 Duo CPU @ 2.0 GHz with 2 GB Random Access Memory (RAM).

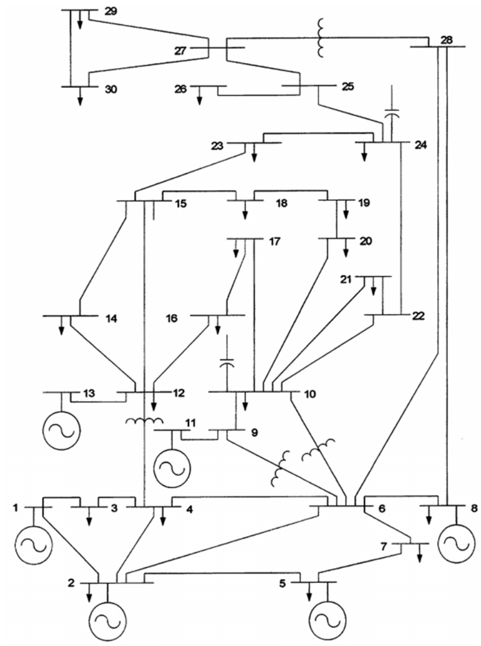

Fig. 2. The IEEE 30-bus system

A. Simulation Results of the IEEE 30-Bus Test System

1) Normal Case

The obtained results from the proposed SFO have been compared with the ones from other methods such as Tabu Search (TS) [26], Evolutionary Programming (EP) [27], DE [28], pSADE_ALM [29], PSO, PSO-TVIW and SOHPSO-TVAC [21, 30], hybrid DA-PSO [31]. The solutions of all methods for the normal case are given in Table I. It can be seen that the total cost obtained by the proposed method is

802.01$/h which is close to the other methods'. As observed from Figure 3, the SFO method has the ability to converge quickly and can reach an optimum solution. From the results comparison it was shown that the proposed SFO is able to find the optimal solution for the OPF problem in the normal case.

TABLE I. RESULT COMPARISON FOR THE NORMAL CASE

Algorithm	Cost ($/h)	Time (s)
TS [26]	802.29	NA
EP [27]	802.62	51.4
DE [28]	802.28	5.02
SADE_ALM [29]	802.40	15.934
pSADE_ALM [29]	802.40	17.295
PSO [30]	802.58	28.208
PSO-TVAC [30]	802.67	11.255
PG-PSO [30]	802.25	11.416
BPSO [21]	803.13	35.15
PSO-TVIW [21]	802.11	33.756
PSO-TVAC [21]	803.56	35.82
SOHPSO-TVAC [21]	802.03	29.43
DA-PSO [31]	802.12	287.13
Proposed SFO	**802.01**	**77.64**

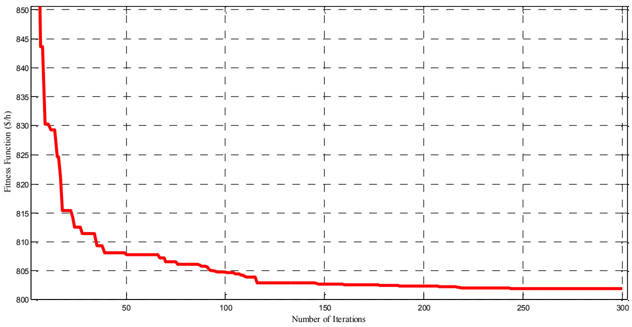

Fig. 3. Convergence characteristics of the SFO algorithm for the IEEE 30-bus system in the normal case

2) *Outage Case*

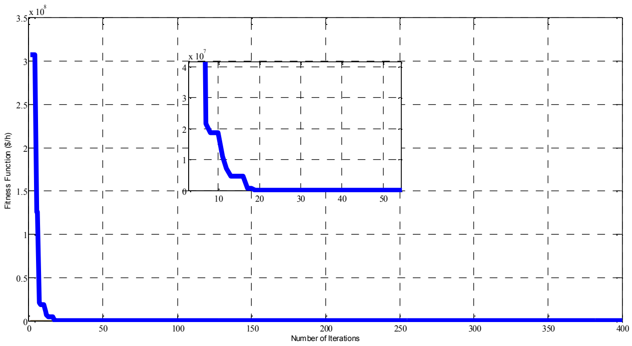

Fig. 4. Convergence characteristics of the SFO algorithm for the IEEE 30-bus system in the outage case

In a power system, if a line is corrupted, its power flow will be shared among the other lines of the system. This will lead to possible overloading of some of the lines. Among the 41 lines in the IEEE 30 bus system, the scenario considers five outage lines that have larger effect on the remaining lines. The optimal solution obtained by the SFO method for the outage cases is given in Table II. The best cost from the SFO method has been compared to those of other known methods in Table II. It can be seen that the total cost obtained by the proposed method was 826.245 which is approximate to the costs obtained from SADE_ALM, pSADE_ALM [29] methods and slightly better than the costs obtained from PSO and PSO-TVAC [30] methods. From Figure 3, it can be seen that the SFO method has the ability to converge quickly and can find the best solution. The result comparison has proved that the proposed SFO is also effective in solving the problem in the outage case.

TABLE II. RESULT COMPARISON FOR THE CASE OF 5 OUTAGE LINES

Algorithm	Cost ($)	Time (s)
SADE_ALM [29]	826.979	46.896
pSADE_ALM [29]	826.242	119.812
PSO [30]	827.186	175.245
PSO-TVAC [30]	828.012	130.59
Proposed SFO	**826.245**	**95.332**

B. *Simulation Results of the IEEE 118-Bus Test System*

Table III gives the fuel costs obtained by SFO and the other optimization techniques in the normal and outage cases under the same conditions. It can be seen that the obtained total fuel cost using SFO in the normal case is 133232.24$/h and for the outage case it is increased by 1238.33$/h. From Table III, it can also be observed that the results using SFO can reach a better solution when compared with many of the other known methods.

TABLE III. RESULT COMPARISON FOR THE IEEE-118 BUS SYSTEM

Algorithm	Cost ($/h)	
	Normal case	Outage case
ICBO [32]	135121.57	136353.31
CBO [32]	135072.99	135297.22
ECBO [32]	135172.26	135582.15
DE [32]	142751.11	158920.80
ABC [32]	135145.18	135759.01
BBO [32]	135272.19	135640.64
Proposed SFO	133232.24	134470.57

Figures 5 and 6 show the convergence characteristics of the minimum fuel cost of the SFO. It can be observed that the SFO has the ability to converge quickly and can find an optimum solution.

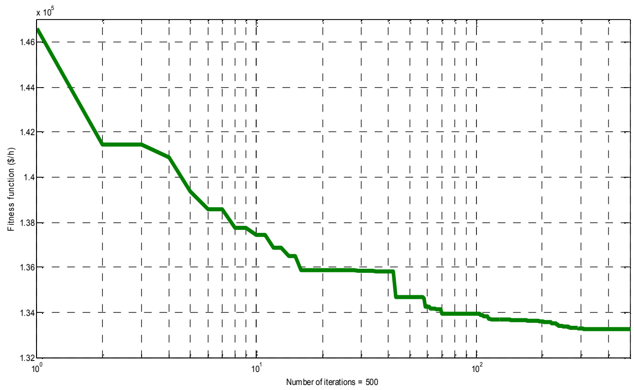

Fig. 5. Convergence characteristics of the SFO algorithm for the IEEE 118-bus system in the normal case

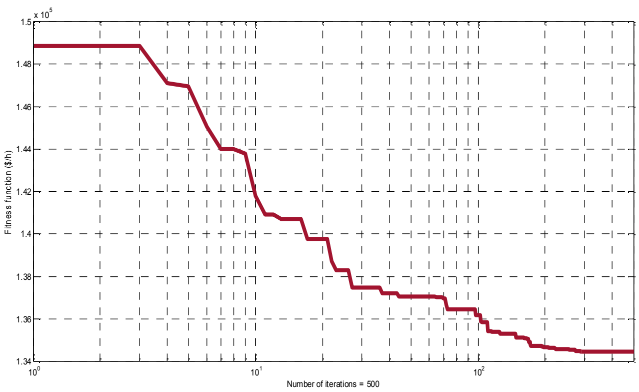

Fig. 6. Convergence characteristics of the SFO algorithm for the IEEE 118-bus system in the outages case

V. CONCLUSION

The competitiveness of the electricity market leads to an increased volume of traded electrical energy between generator and distribution companies which may cause unpredicted power flow through some transmission lines. This may lead to situations in which the transmission network is not able to accommodate all the desired transactions due to violations of some system security constraints. Thus, the Independent System Operators are facing many challenges in terms of normal system operation while trying to obtain economic benefits and security. SCOPF is a nonlinear optimization problem with many complex constraints. This paper proposes the Sunflower Optimization (SFO) algorithm for solving the SCOPF problem. The proposed method has been tested on the IEEE 30-bus and IEEE 118-bus systems for normal and outage cases. The result comparison revealed that the proposed SFO is capable of providing better solution quality than many other optimization approaches. Therefore, the proposed SFO can be an extremely effective alternative approach for solving the SCOPF problem.

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