Optimal Power Flow solution using Spotted Hyena Optimization Algorithm

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Abstract

This paper presents an efficient and reliable metaheuristic algorithm named as Spotted Hyena Optimization (SHO) algorithm which is being inspired by the social hierarchy and hunting behavioral nature of spotted hyenas. The proposed SHO algorithm is dwelt for obtaining optimal setting of the control variables of the OPF problems. Basically, SHO can deals to solve problems bounded by constraints and come out with better optimum solutions in less computational time than other optimization techniques. The proposed approach has been examined on the standard IEEE 14-bus and IEEE 30-bus test systems with objectives including generator fuel cost and transmission line losses. The results obtained are promising and highlights the effectiveness and superiority of the proposed approach in comparison to the existing algorithms.

Keywords: *Optimal Power Flow (OPF), Spotted Hyena Algorithm (SHO) Algorithm, generation fuel cost, transmission line losses.*

1. Introduction

The problem OPF has been under wide consideration over past decades and identified as main tool for optimal operations and planning of modern power systems. Mainly objective of the OPF problem is to optimize the objective functions such generation fuel cost and transmission line losses. OPF problem is being solved with bounded by specific constraint limits and optimal setting of control variables which includes the tap changing transformers, the generator real powers, the generator bus voltages and the reactive power generations of shunt compensating sources whereas state variables involving the generator reactive power, load bus voltages and line flows of the network.

OPF problem is considered as a highly constraint bounded, large-scaled non-linear non-convex optimization problem. Initially, Dommel and Tinney (1968) in Ref. [1] formulated the OPF problems, after then it became keen topic for research. For solving the OPF problem many traditional optimization methods such as linear programming (LP), non-linear programming (NLP), quadratic programming (QP), Newton-based techniques and interior point methods (IPM) had been carried out by researchers in [2]-[7] but these methods could not deal with large- scale system and fails to results in global solutions. Because of these shortcomings researches got directed towards emergence of metaheuristic algorithms which includes Genetic Algorithm (GA) [8], Particle Swarm Optimization (PSO) [9], Evolutionary Programming (EP) [10], Biogeography Based Optimization (BBO) [11], Moth Flame Algorithm [12], Criss-Cross Algorithm (CCA) [13], Fruit Fly Algorithm (FFA) [14], Ant Colony Algorithm (ACO) [15] and many more briefed in Ref. [16]. These algorithms are implemented for solving OPF problems with controlling a balance between exploration and exploitation.

Similarly, a novel algorithm Spotted Hyena Optimization (SHO) is being introduced in Ref. [17] suggests better solutions as compared to existing algorithm as shown in literature. Benchmark test functions are effectively minimized by the proposed algorithm as compared to other algorithm, keeping this in consideration in this paper SHO is implemented to solve the OPF problems for IEEE-14 bus and IEEE 30-bus test systems. This paper presents that SHO is an effective and feasible technique as compared to literature available.

2. Problem Formulation

Optimal Power Flow (OPF) deals to solve the steady state problem of electric power systems through minimizing the objective functions with the consideration of constraints simultaneously. Mathematically OPF is represented by:

$$\text{Min } F_p(x,y) \qquad \forall p = 1,2,.......t$$

$$\text{Subject to:} \quad g(x,y) = 0,$$

$$h(x,y) \leq 0$$

where, ‘g’ and ‘h’ are the equality and inequality constraints respectively, ‘x’ is the state vector of dependent variables and ‘y’ is the control vector of system and t is the total number of objectives functions.

The state vector may be represented by:

$$x^T = [P_{g,1}, V_{l,1} .... V_{l,NL}, Q_{g,1} .... Q_{g,NG}, S_{l,1} .... S_{l,NT}]$$

The control vector may be represented by:

$$y^T = [P_{g,2} ..... P_{g,NB}, V_{g,1} .... V_{g,NB}, Q_{SH,1} .... Q_{SH,NC}, T_1 .... T_T]$$

Where $P_{g,1}$ is the real power, $V_{l,1}$ is the load bus voltage, , $Q_{g,1}$ is the reactive power of generator, $S_{l,1}$ is the apparent power of generator $V_{g,1}$ is the generator voltage of slack bus. NL, NG, NT, NC and T are the total number of PQ buses, PV buses, transmission lines, shunt compensators and off-nominal tap transformers respectively.

2.1. Objective Functions

In this paper, two single objective functions are minimized, which are mathematically expressed below:

a. Generation fuel cost minimization

$$F_1 = min(F_p(P_{g,m})) = \sum_{m=1}^{NGB} x_m P_{g,m}^2 + y_m P_{g,m} + z_m \,\$/h \qquad (1)$$

where, x_m, y_m and z_m are the fuel cost coefficients of m^{th} unit.

b. Transmission line losses minimization

$$F_3 = min(P_{loss})) = \sum_{m=1}^{NTL} P_{loss,m} MW \tag{2}$$

2.2. Constraints

The equality and in-equality constraints are as follows:

a. Equality constraints

$$\sum_{m=1}^{NGB} P_{g,m} - P_D - P_L = 0\ , \quad \sum_{m=1}^{NGB} Q_{g,m} - Q_D - Q_L = 0$$

b. Inequality Constraints

(i). Generator constraints

$$V_{g,m}^{min} \le V_{g,m} \le V_{g,m}^{max} \text{ and}$$
$$Q_{g,m}^{min} \le Q_{g,m} \le Q_{g,m}^{max} \qquad \forall m \in NG$$

(ii). Voltage at bus and discrete transformer tap settings

$$V_{g,m}^{min} \le V_{g,m} \le V_{g,m}^{max} \text{ and}$$
$$T_m^{min} \le T_m \le T_m^{max} \qquad \forall m \in T$$

(iii). Active power generation limits

$$P_{g,m}^{min} \le P_{g,m} \le P_{g,m}^{max} \qquad \forall m \in NG$$

(iv). Reactive power supply by the capacitor banks

$$Q_{SH,m}^{min} \le Q_{SH,m} \le Q_{SH,m}^{max} \qquad \forall m \in NC$$

(v). Transmission line loadings

$$S_{l,m} \le S_{l,m}^{max} \qquad \forall m \in NT$$

3. Spotted Hyena Algorithm

Spotted hyenas which are scientifically called as Crocuta, they are the large carnivore's dogs. They basically presents in areas of savannas, grasslands, sub-deserts and forests of Africa and Asia. They have total 35-40 years of life span in which they spend 10–15 years in forest and remaining 25 years in imprisonment. They are very efficient in hunting, intelligent and considered as the most social animal. They have the rigorous capability to rebel for food and territory [17]. They are also known as Laughing Hyena as their sounds are similar to the human laugh. The main steps of SHO are inspired by hunting behavior of spotted hyenas.

3.1. Steps of mathematically modeling of hunting mechanism of Spotted Hyena

Hunting mechanism is performed in four main steps discussed below:

3.1.1. Encircling prey

Initial location of prey is already known to spotted hyenas and aware of how to encircle them as shown in **Figure 1.** To begin with spotted hyenas which is near by the target prey is considered to be the best solution initially and according to it the other spotted hyenas will update their positions. Mathematically this natural phenomenon is modeled by the following equations:

$$\vec{D}_{ph} = |\vec{C}.\vec{P}_p(t) - \vec{P}_{sh}(t)| \qquad (3)$$

$$\vec{P}_{sh}(t+1) = \vec{P}_p(t) - \vec{E}.\vec{D}_{ph} \qquad (4)$$

Where, $\vec{D}_{ph}$ is the distance between prey and spotted hyenas, $\vec{C}$ and $\vec{E}$ are the co-efficient vectors of position vector of prey $\vec{P}_p$, $\vec{P}_{sh}$ is the position vector of spotted hyenas and t is the current iteration. The co-efficient vectors can be calculated as:

$$\vec{C} = 2.\vec{d_1} \qquad (5)$$

$$\vec{E} = 2\vec{k}.\vec{d_2} - \vec{k} \qquad (6)$$

Where, $\vec{k}$ =5-(Current iteration×(5/Maximum iteration)) (7)

where, $\vec{k}$ initiates more exploitation as its value decreases from 5 to 0 as iterations increases over the period, $\vec{d_1}$ and $\vec{d_2}$ are the random vectors in the range of [0,1].

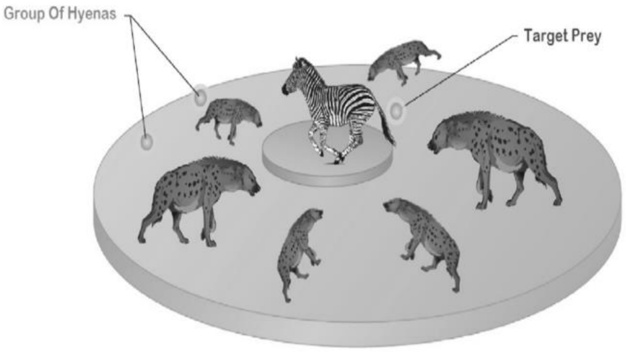

Figure 1. Encirclement of target prey by Spotted Hyenas

3.1.2. Hunting

Spotted hyenas basically form a clan which possess of trusted pals and has the capability to identify the location of prey. Selected best spotted hyena has the information for the location of prey and other spotted hyenas forms a cluster in the direction of best. The following equations are proposed to elaborate the mechanism:

$$\vec{D}_{ph} = |\vec{C}.\vec{P}_{fb}(t) - \vec{P}_{osh}(t)| \qquad (8)$$

$$\vec{P}_{osh} = \vec{P}_{fb} - \vec{E}.\vec{D}_{ph} \qquad (9)$$

$$\vec{G} = \vec{P}_{osh} + \vec{P}_{osh+1} + \ldots\ldots + \vec{P}_{osh+NSH} \qquad (10)$$

Where, $\vec{P}_{fb}$ and $\vec{P}_{osh}$ defines the position of first best and other spotted hyenas, $\vec{G}$ is a group of cluster of optimal solutions, NSH is the total number of spotted hyenas which is represented as:

$$NHS = count(\vec{P}_{fb} + \vec{P}_{fb+1} + ... + \vec{P}_{fb+\vec{M}}) \qquad (11)$$

Where, $\vec{M}$ is a random vector in [0.5, 1] and *count* represents the counting of number of solutions.

3.1.3. Attacking prey

The mathematical formulation for attacking the prey is as follows:

$$\vec{P}_{sh}(t+1) = \vec{G} / NSH \qquad (12)$$

It saves the best solution obtained and regards of which other spotted hyenas update their positions.

3.1.4. Search for prey

Usually, spotted hyenas search the prey with respect to its cluster vector $\vec{G}$. For searching and attacking prey, the spotted hyenas start diverging from each other. Furthermore, $\vec{E}$ is deciding vector for the positioning of spotted hyenas as if |E| > 1 reflects movement away from prey while |E| < 1 reflects movement towards the prey. Then $\vec{C}$ is also a vector with random values which enhances the exploration and helps to avoid local optima.

Finally, the SHO algorithm is terminated by satisfying termination criteria.

3.2. Pseudo code and flowchart for the SHO algorithm

The steps of SHO are summarized as follows:

START

Step 1: Read bus data, line data and generation data of considered power system.

Step 2: Initialize the parameters of the proposed algorithm such as number of spotted hyenas $\vec{P}_i$ and maximum number of iterations.

Step 3: Initialize vectors k, C, E, and NSH using:

k=5-(Current iteration× (5/Maximum iteration))

$$\vec{C} = 2.\vec{d}_1$$

$$\vec{E} = 2\vec{k}.\vec{d}_2 - \vec{k}$$

Step 4: Calculate the initial position of each search agents and distance between prey and search agents using:

$$\vec{D}_{ph} = |\vec{C}.\vec{P}_p(t) - \vec{P}_{sh}(t)|$$

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$\vec{P}_{sh}(t+1)=\vec{P}_{p}(t)-\vec{E}.\vec{D}_{ph}$

Step 5: Identify the First best search agent $\vec{P}_{fb}$.
while(t<t_max)
    for (each $\vec{P}_{i}$)
        Step 6: Update the position of current search agent by using equations:

        $\vec{D}_{ph}=|\vec{C}.\vec{P}_{fb}(t)-\vec{P}_{osh}(t)|$
        $\vec{P}_{osh}=\vec{P}_{fb}-\vec{E}.\vec{D}_{ph}$
        Define cluster using $\vec{G}=\vec{P}_{osh}+\vec{P}_{osh+1}+......+\vec{P}_{osh+NSH}$
        and $NHS=count(\vec{P}_{fb}+\vec{P}_{fb+1}+......+\vec{P}_{fb+\vec{M}})$.
        Then
        $\vec{P}_{sh}(t+1)=\vec{G}/NSH$
    end for

    Step 7: Update k, C, E, NSH.
    Step 8: Check (search agent goes beyond limit) and then adjust it.
    Step 9: Update the fitness function.
    Step 10: Update $\vec{P}_{fb}$ value if it is better than the previous value.
    Step 11: Update cluster $\vec{G}$ against search agent fitness.
    Step 12: t=t+1

end while
Return best optimum value obtained
END
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Flowchart of SHO is shown in **Figure 2.**

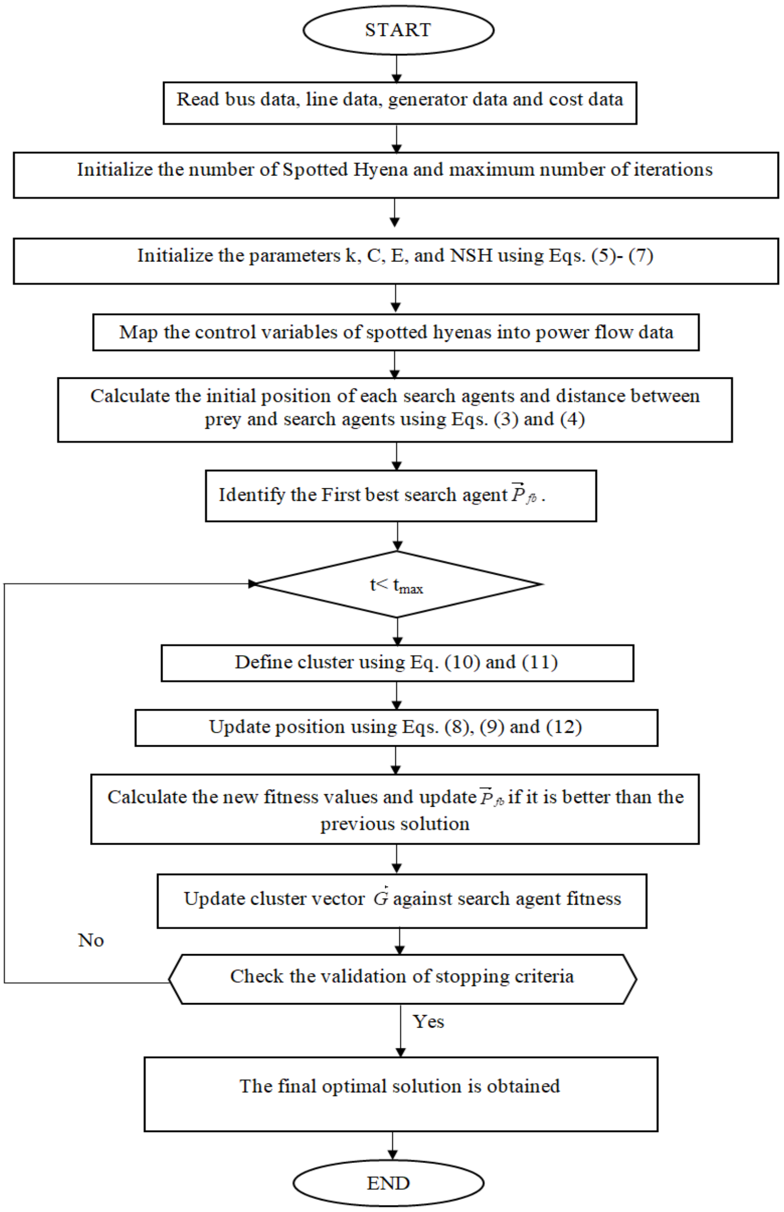

Figure 2. Flowchart of SHO

4. Results and Analysis

In this paper, novel SHO algorithm is implemented to solve an OPF problem which includes objectives generation fuel cost and transmission line losses mentioned in Eqs. (1) and (2) for standard IEEE-14 bus and IEEE 30-bus test systems.

4.1. Illustrative Example-1

In standard IEEE 14-bus system, 5 generators placed at buses 1, 2, 3, 6 and 8; three off-nominal tap ratio transformers placed between the buses 4-7, 4-9, and 5-6 and shunt capacitor at bus 9. Relevant data is taken from Ref. [18].

OPF problems are being solved using proposed algorithm and it can be seen from **Table 1** for considered objectives that, values result out to be less as compared to the optimal solutions obtained using other existing algorithms. We can see that generation fuel cost, and transmission line losses obtained using SHO are 714.1804$/h and 3.16723MW respectively which is best optimal values obtained for IEEE-14 bus system.

Table 1. OPF solution for considered objective functions for IEEE-14 bus system

Variables	Generation fuel cost, $/h			Transmission line losses, MW		
	HSCA[19]	**HALO[20]**	**SHO**	**HSCA[19]**	**HALO[20]**	**SHO**
PG1, MW	161.4779	177.7548	176.5512	75.0517	65.42774	39.84451
PG2, MW	46.8931	47.26885	48.12015	112.0794	69.7641	106.8258
PG3, MW	20.000	22.34667	21.54344	43.9330	60	46.79028
PG6, MW	33.9437	14.92658	16.00888	23.2024	50	46.29497
PG8, MW	5.000	5.066718	5.029755	9.6166	17.25803	22.41164
VG1, p.u.	1.05381	1.098924	1.1	1.0560	1.009454	1.06347
VG2, p.u.	0.9000	0.905943	0.9	0.9000	0.9	1.036147
VG3, p.u.	1.0079	1.1	1.1	1.1000	0.979317	1.036365
VG6, p.u.	0.9783	1.1	1.1	1.0097	0.919835	1.074251
VG8, p.u.	1.1000	1.1	0.907121	1.1000	1.058363	1.042082
Tap 4-7, p.u.	1.0210	1.1	0.948271	1.1000	0.952082	1.060042
Tap 4-9, p.u.	0.9000	1.044831	0.944797	1.0114	0.9	0.916784
Tap 5-6, p.u.	1.0670	1.080909	0.956958	0.9708	0.9	1.024826
Qc 9, p.u.	5.000	17.49418	29.9244	29.5561	23.57283	17.83213
Generation fuel cost, $/h	**721.8330**	**715.588**	**714.1804**	**862.8203**	**881.7387**	**904.0419**
Transmission line losses, MW	**8.314585**	**8.363622**	**8.253427**	**4.8830**	**3.449867**	**3.167223**

Hence, SHO is effective for solving OPF problems. Further we can also justify the performance of proposed algorithm by considering the convergence curve shown in **Figure 3-4.** We can clearly observe that convergence starts with lesser value and final result obtained very early as compared to HALO and HCSA.

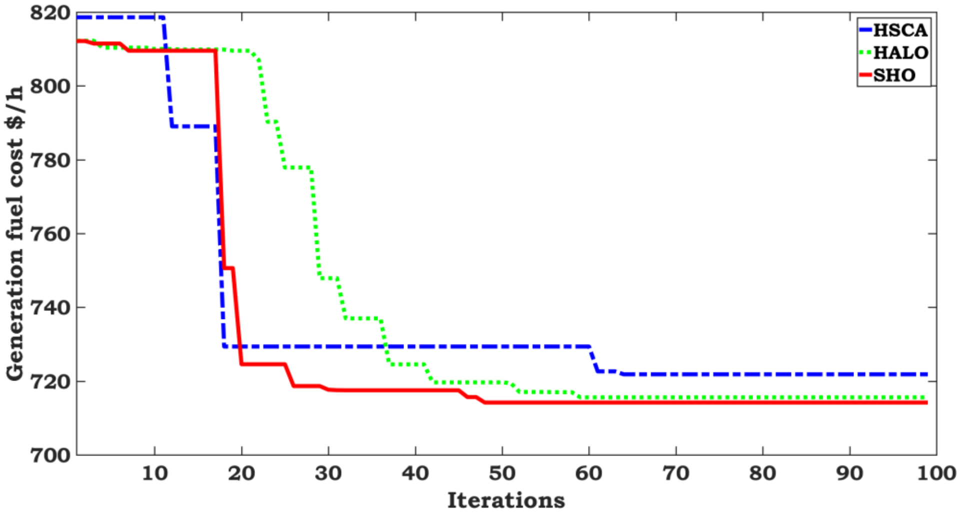

Figure 3. Convergence curve of generation fuel cost, $/h

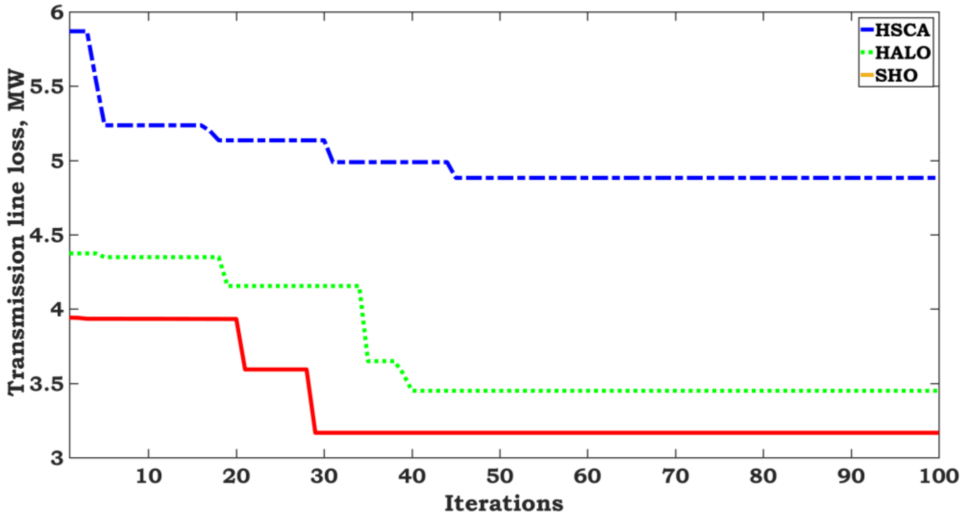

Figure 4. Convergence curve of transmission line losses, MW

4.2. Illustrative Example-2

The SHO algorithm has been verified on IEEE-30 bus system by solving the OPF problems. Generally, IEEE- 30 bus system consists of 6 generators placed on buses 1, 2, 5, 8, 11 and 13, four off-nominal tap ratio transformers placed between the buses 6-9,6-10, 4-12, 27-28 and two shunt capacitors at buses 10 and 24. For each objective, proposed algorithm has run up to 100 iterations. Relevant data is taken from Ref. [21].The result obtained for proposed algorithm has been compared with the existing literature values.

Generation fuel cost and transmission line losses are minimized by proposed algorithm and from **Table 2**, it can easily be justified that the proposed algorithm minimizes the objective to the best minimum value as compare to other existing algorithms. It can be seen that generation fuel cost and transmission line losses achieved are 800.86 $/h 3.5366 MW and respectively which are minimum obtained optimal values. Thus, the proposed algorithm gives the better results. **Figure 5-6** shows the convergence curve for generation fuel cost and transmission line losses, from which we can conclude that proposed algorithm helps the convergence to reach the best final value in less iteration as compared to other existing algorithms.

Table 2. OPF solution for considered objective functions for IEEE-30 bus system

Variables	**Generation fuel cost, $/h**			**Transmission line losses, MW**		
	HSCA[22]	**PSO[22]**	**SHO**	**HSCA[22]**	**PSO[22]**	**SHO**
PG1, MW	176.87	178.556	175.865	63.7401	64.326	67.486
PG2, MW	49.8862	48.6032	47.4864	68.2844	67.7681	70.352
PG5, MW	21.6135	21.6697	21.7241	50	50	40.4208
PG8, MW	20.8796	20.7414	18.6053	35	35	25.7218
PG11, MW	11.6168	11.7702	13.3922	30	30	21.2841
PG13, MW	12	12	12.602	40	40	35.1543
VG1, p.u.	1.057	1.1	1.097	1.0563	1.06	1.0756
VG2, p.u.	1.0456	0.9	1.087	1.0082	1.0448	0.8645
VG5, p.u.	1.0184	0.9642	1.059	1.0354	1.0062	1.0549
VG8, p.u.	1.0265	0.9887	1.070	1.0393	1.0086	1.0141
VG11, p.u.	1.057	0.9403	0.97	1.057	1.0819	0.9834
VG13, p.u.	1.057	0.9284	1.099	1.0377	1.07079	1.0963
Tap 6-9, p.u.	1.0254	0.9848	1.02	1.0197	0.9875	0.9565
Tap 6-10, p.u.	0.9726	1.0299	0.945	0.9594	0.9596	0.9752
Tap 4-12, p.u.	1.006	0.9794	1.0086	0.9196	0.93	0.9584
Tap 28-27, p.u.	0.9644	1.0406	0.97887	0.9796	0.9699	0.9798
Qc 10, p.u.	25.3591	9.0931	25.005	22.7301	25	24.14
Qc 24, p.u.	10.6424	21.665	6.65638	24.5998	21.985	17.54
Generation fuel cost, $/h	**802.034**	**803.454**	**800.86**	**946.5282**	**945.84924**	**936.455**
Transmission line losses, MW	**9.466955**	**9.9403**	**9.78778**	**3.6245**	**3.6943449**	**3.5366**

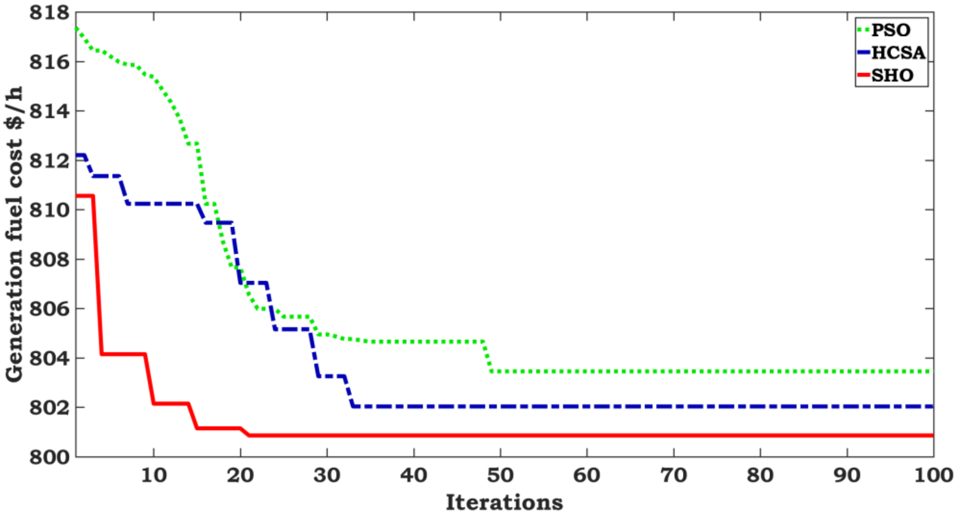

Figure 5. Convergence curve of generation fuel cost, $/h

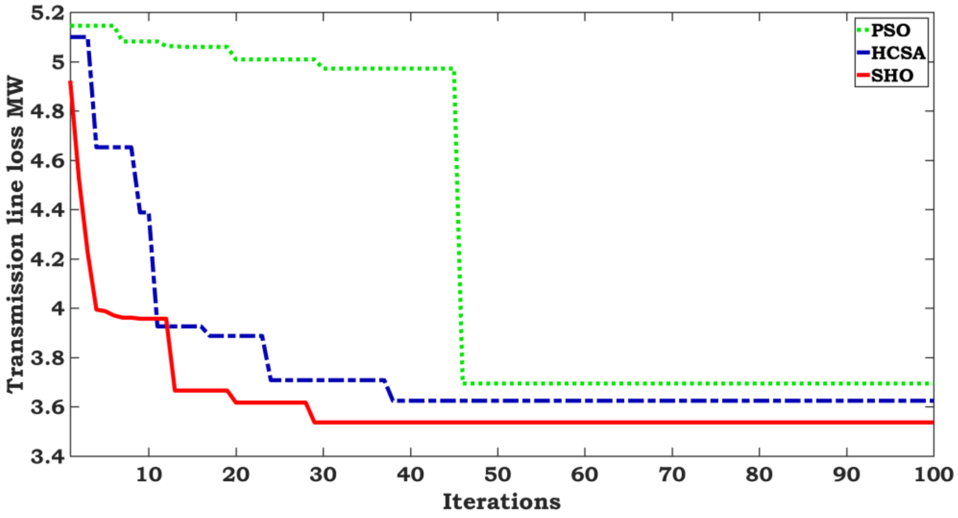

Figure 6. Convergence curve of transmission line losses, MW

5. Conclusion

In this paper, a novel algorithm is used named as Spotted Hyena Optimization (SHO) algorithm which is inspired by the social and hunting behavior of spotted hyena. The proposed algorithm is implemented to solve OPF problems of power systems. SHO algorithm's performance is observed on standard IEEE 14-bus and IEEE 30-bus test systems by solving the considered objective functions which are generation fuel cost and transmission line losses. Hence it is being observed that SHO algorithm minimizes the functions to the best values and those values are achieved in less number of iteration as compared to the other existing algorithms. Thus, SHO is effective and reliable algorithm which can optimally solve the OPF problems. Further, we can implement the proposed algorithm to the larger power systems and multi-objective problems.

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