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SOLUTION OF SECURITY CONSTRAINED OPTIMAL POWER FLOW USING HONEY BEE MATING OPTIMIZATION

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Abstract- As a nonlinear, non-convex and large scale optimization problem including both continuous and discrete control variables, security-constrained optimal power flow (SC-OPF) is one of the most important power system problems which need a superior optimization technique to be effectively solved. Inspired by the mating process of honey bees, honey bee mating optimization (HBMO) is a recently invented swarm-based search algorithm owning the potential of finding optimal or close-to-optimal solution. This paper studies the effectiveness of HBMO algorithm to tackle the complexity of SC-OPF problem considering both prohibited operating zones and valve point loading effects. Simulation results show that HBMO produces better results than the other techniques on different test systems.

Keywords: SC-OPF, HBMO, IHBMO, Power System Operation, Optimization.

I. INTRODUCTION

Electric power grid is regarded as the most complex man-made system [1]. In order to optimally analyze, monitor and control different aspects of such sophisticated system developing special tools is essential. Optimal power flow (OPF) is the backbone tool of this system that has been extensively researched. The ultimate aim of OPF is to find the optimal settings of a power system that optimize a certain objective function while satisfying the constraints of the components and the system. Most often, the objective function of OPF is the minimization of the overall fuel cost function.

Difficult nature of OPF stems from this fact that it is a non-linear, non-convex and large scale optimization problem including both continuous and discrete control variables. Continuous control variables are real power outputs and voltages while discrete ones are transformers tap setting and reactive injections. If non-linear security constraints of the power system are added to the OPF, resulting in security-constrained OPF (SC-OPF), even a more difficult optimization problem is acquired. Hence, to effectively solving SC-OPF problem, a capable optimization technique should be used.

Earlier solution methods for OPF problem include mathematical programming approaches like Newton method [2], linear programming (LP) [3], nonlinear programming (NLP) [4], quadratic programming (QP) [5], and interior point (IP) methods [6]. Mathematical programming approaches that require continuity, convexity and differentiability conditions for being applicable, usually involve heavy computations, are local in nature and converge to a local solution rather than a global one if the initial guess is located at the vicinity of a local solution. As a result, using more efficient approaches to conquer the difficulty of SC-OPF and obtain more promising results is necessity.

Owing to their great potential to find optimal or close-to-optimal solutions, metaheuristic optimization algorithms have attracted significant attention to solve OPF problem. These techniques can be addressed by genetic algorithm (GA) [7], particle swarm optimization (PSO) [8], differential evolution (DE) [9], Tabu search (TS) [10], bacterial foraging (BF) [11], simulated annealing (SA) [12], and shuffle frog-leaping algorithm (SFLA) [13]. These algorithms can be considered as suitable choices for solving OPF problem because they have global search power, are derivative-free, own constraint handling capacity, and don't have any restriction on the shape of the objective function [14-26].

In spite of the performed researches in the OPF area, this problem is still open and more efficient solution methods are demanded because of its importance and complexity. In addition, SC-OPF is a more comprehensive and more recent concept than OPF and fewer studies on it can be found in the literature. Honey bee mating optimization (HBMO) is a recently invented meta heuristic algorithm [14] attempting for simulation of the mating process of honey bees to design optimum searching strategies for finding the solution of complex optimization problems. Simplicity, easy implementation and high efficiency to find optimal or near optimal solution have led to application of HBMO in different areas.

In HBMO, the best solution of the swarm found so far is called the queen. The queen flights away from the hive and the drones of the swarm follow her. They attempt to mate with the queen by a probabilistic approach and produce a population of broods. It is expected as the algorithm progresses, the good quality regions of the search space are found and the algorithm converges to the optimal solution.

This paper proposes honey bee mating optimization (HBMO) as an efficient candidate for solving the SC-OPF problem. In the SC-OPF problem both prohibited operating zones and valve-point loading effects are taken into account. In order to make a decision on the performance of HBMO, a comprehensive comparison is made between the performance of the proposed algorithm and the results obtained by the other methods reported in the literature. The rest of this paper is arranged as follows: Section II provides formulation of SC-OPF problem; In Section III, HBMO is explained in detail; Simulation results and discussions are presented in Section IV and finally, conclusion is stated is Section V.

II. FORMULATION OF SC-OPF

The objective function and constraints that make the SC-OPF are introduced below.

A. Objective Function

The ultimate objective of SC-OPF problem is to minimize the total cost function of thermal generating units F, defined by Equation (1).

$$F = \sum_{i=1}^{NG} FC_i \tag{1}$$

where, F is the total generation cost, FC_i is the fuel cost function of ith generator, and NG denotes the number of the generators.

In general, a quadratic function (convex and differentiable) is used as the fuel cost of thermal generation units.

$$FC_i\left(P_{G_i}\right) = a_i P_{G_i}^2 + b_i P_{G_i} + c_i \tag{2}$$

where, P_{Gi} specifies the active generation of ith unit and a_i, b_i and c_i are cost coefficients for ith generator.

In multi-valve steam turbines, the valve opening process produces a ripple-like effect in the heat rate curve of generators. Figure 1 shows valve-point loading effect on the fuel cost characteristic. By considering the valve-point loading effect, a sinusoidal term is incorporated in Equation (2). Hence, Equation (2) is modified and a more accurate cost function is defined by Equation (3).

$$FC_i\left(P_{G_i}\right) = a_i P_{G_i}^2 + b_i P_{G_i} + c_i + \left| e_i \sin(f_i (P_{G_i}^{\min} - P_{G_i})) \right| \tag{3}$$

where, e_i and f_i are non-smooth fuel cost coefficients and $P_{G_i}^{\min}$ is minimum power generation limit of ith generator.

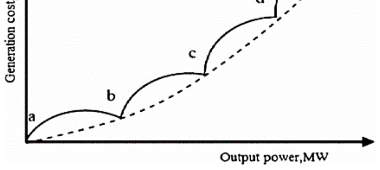

Figure 1. Valve-point loading effect on the fuel cost characteristic [13]

B. Constraints

B.1. Equality Constraints

These constraints are non-linear AC power flow equations define by Equations (4) and (5).

$$P_{G_i} - P_{D_i} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \tag{4}$$

$$Q_{G_i} - Q_{D_i} + \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin\left(\theta_{ij} - \delta_i + \delta_j\right) = 0 \tag{5}$$

where, P_{Gi} and Q_{Gi} are the real and reactive power outputs injected at ith bus, respectively, P_{Di} and Q_{Di} are the load demand at the same bus, and the elements of the bus's admittance matrix are given by $|Y_{ij}|$ and θ_{ij}.

B.2. Inequality Constraints

B.2.1. Prohibited Operating Zones

Faults in the generating units or in the associated auxiliaries such as boilers and feed pumps may result in instability in certain ranges of the generator power output. These ranges are prohibited from operation and fuel cost function of generators with prohibited zones will be discontinuous. To avoid prohibited operating zones the following constraint must be regarded.

$$P_{G_i} \in \begin{cases} P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{LB_1} \\ P_{G_i}^{UB_{k-1}} \le P_{G_i} \le P_{G_i}^{LB_k} \\ P_{G_i}^{UB_k} \le P_{G_i} \le P_{G_i}^{\max} \end{cases} \tag{6}$$

where, $P_{G_i}^{LB_k}$ and $P_{G_i}^{UB_k}$ are the lower and upper bounds of the kth prohibited operating zone for ith unit and k denotes the prohibited zone's index.

B.2.2. Active, Reactive Power Outputs of Generators

Power operating limits are defined by Equations (7) and (8).

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}, \quad i = 1, 2, ..., NG \tag{7}$$

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}, \quad i = 1, 2, ..., NG \tag{8}$$

where, min and max indexes denote the lower and upper allowable limit of power generation for ith generator, respectively.

B.2.3. Bus Voltage Magnitude and Branch Flow Limits (Static Security Constraints)

At each bus of the network, the following criterion should be considered.

$$V_i^{\min} \le V_i \le V_i^{\max}, \quad i = 1, 2, ..., NB \tag{9}$$

where, NB is the number of the network buses.

The constraint of the transmission lines loading is as follows.

$$S_{L_i} \le S_{L_i}^{\max}, \quad i = 1, 2, ..., NL \tag{10}$$

where, NL is the number of the network lines.

B.2.4. Transformer's Tap Setting Constraint

For each transformer, the discrete tap setting constraint is as follows:

$$T_i^{\min} \le T_i \le T_i^{\max}, \quad i = 1, 2, ..., NT \tag{11}$$

where, NT is the number of the network transformers.

B.2.5. Reactive Power Injection Constraint

The discrete reactive power injections due to capacitor banks should satisfy the following criterion.

$$Q_{C_i}^{\min} \le Q_{C_i} \le Q_{C_i}^{\max}, \quad i = 1, 2, ..., NC \tag{12}$$

where, NC is the number of the capacitor banks.

The decision variables of the SC-OPF are both continuous and discrete. The decision variables vector can be shown as Equation (13).

$$X = \left[P_{G_2}, ..., P_{G_{NG}}, V_{G_1}, ..., V_{G_{NG}}, T_1, ..., T_{NT}, Q_1, ..., Q_{NC} \right] \tag{13}$$

In Equation (13), P_{Gi} and V_{Gi} are continuous variables while T_i and Q_i are discrete ones. As the vector shows, the active power of all the network generators is included except the slack bus (P_{G1}), because the generation of the slack bus is a dependent variable, which is determined based on the system load and the generation of the other units. As a result, number of the decision variables which needs to be determined is $NV = (NG - 1) + NG + NT + NC$. The formulation of the SC-OPF shows that it is a nonlinear, non-convex, non-differentiable and non-smooth optimization problem with discontinuous search space. Hence, SC-OPF is a complex and challenging optimization problem, which needs a superior optimization technique to be effectively solved.

III. USING HBMO ALGORITHM FOR SC-OPF

Originally proposed by Afshar et al. [14], HBMO is a swarm-based search algorithm, which tries to mimic the behavior of honey bees during mating process to find the global solution of optimization problems. HBMO contains a swarm of bees where there are three kinds of bees: queen (reproductive female), drones (males) and workers (non reproductive females). The steps of this algorithm are as follows [15].

Step 1- Initialization to a swarm of bees: A population including N bees is randomly generated in the search space. Each bee is a feasible solution of SC-OPF and is specified by a vector, X.

Step 2- Calculation of the objective function: The objective function value for each individual is calculated. To handle the AC power flow constraints, AC power flow is executed in the solution process instead of adding its equality constraints to the optimization problem. By this approach, the tight equality constraints of the SC-OPF are processed by an AC power flow solution algorithm and the optimization algorithm should only handle the inequality constraints. Note that the proposed algorithm is implemented in the MATLAB environment and there are efficient computer codes in MATLAB for the solution of AC power flow.

Step 3- Sorting the individuals: In this step, the individuals are increasingly sorted based on objective function values.

Step 4- Selection of queen: The bee with the best quality (minimum objective function value) is selected as the swarm's queen, $\overline{X}_{best}$.

Step 5- Generation of the queen's speed: The speed of the queen is adjusted by Equation (14).

$$S_{queen} = S_{\min} + r(S_{\max} - S_{\min}) \tag{14}$$

where, S_{queen} is the queen's speed, r denotes a random number uniformly distributed between 0 and 1, and $S_{\min}$ and $S_{\max}$ are the minimum and maximum ranges of the speed, respectively.

Step 6- Selection of the drones: A predefined number of the sorted bees are selected as the drones.

Step 7- Generation of the queen's spermatheca matrix: The queen flies with her maximum speed to perform the mating flight. At this stage, she randomly selects a drone from the population of the drones. The queen mates with the selected drone probabilistically using the annealing function as follows:

$$P_m = \exp(-\Delta f / S(t)) \tag{15}$$

where, P_m is the mating probability and Δf is the difference between the drone and the queen objective function values. A random number uniformly distributed between 0 and 1 is then generated and compared with P_m. If it is less than the calculated probability, the queen stores the drone's sperm in her spermatheca. Otherwise, the queen is not interested in storing the sperm of that drone in her spermatheca. After that, another drone is randomly selected and this process continues until the queen's speed updated by Equation (16), reaches to her minimum or the spermatheca size, N_{sperm}, becomes full.

$$S(t+1) = \alpha S(t) \tag{16}$$

where, S is the queen's speed, $S(t+1)$ denotes the next speed and α is a random number uniformly distributed between 0 and 1.

Step 8- Breeding process: Based on mating between the queen and the drones stored in the queen's spermatheca a population of broods is produced. Equation (17) defines the generation of the jth brood.

$$\overline{Brood}_j = \overline{X}_{best} + \beta \times (\overline{X}_{best} - \overline{Sp}_j) \tag{17}$$

where, $\overline{X}_{best}$ is the queen, β is is a random number uniformly distributed between 0 and 1, and Sp_j denotes the jth individual from the queen's spermatheca [16].

Step 9- Feeding the queen and the produced broods using the royal jelly: The workers are employed to feed the queen and the produced broods via the royal jelly. For this aim, mutation operator is used to improve the quality of the queen and the broods. This process helps to conduct local search.

Step 10- Calculation of the objective function value for the new produced broods: The quality of the mutated broods is computed. If a mutated brood has better quality than the individual, the mutated brood is replaced with it.

Step 11- Checking the termination criterion: If the termination criterion is met, the best found individual is returned as the SC-OPF solution. Otherwise, N best individuals among the population and the broods are selected as new swarm and Steps 3 to 11 are repeated until the termination criterion, which is a predefined number of iterations, N_{iter}, is reached.

Like other optimization algorithms, HBMO suffers from trapping in local optima. As a powerful strategy, mutation diversifies the HBMO population and improves its performance by preventing premature convergence to local optima. A new mutation factor has been introduced and validated in [17]. To apply this mutation factor three drones (Sp_{m1}, Sp_{m2}, Sp_{m3}) are randomly selected from queen's spermatheca so that $m_1 \neq m_2 \neq m_3$. Then, the following formulas are performed.

$$X_{improved,1} = Sp_{m1} + r_1(Sp_{m2} - Sp_{m1}) \quad (18)$$

$$X_{improved,1} = [x^1_{im1}, x^2_{im1}, ..., x^n_{im1}] \quad (19)$$

$$X_{Brood,1} = [x^1_{br1}, x^2_{br1}, ..., x^n_{br1}] \quad (20)$$

$$x^i_{br1} = \begin{cases} x^i_{im1} & \gamma_1 \leq \gamma_2 \\ Sp^i_{m1} & \text{otherwise} \end{cases} \quad (21)$$

$$X_{improved,2} = \overline{X}_{best} + r_2(Sp_{m2} - Sp_{m1}) \quad (22)$$

$$X_{improved,2} = [x^1_{im2}, x^2_{im2}, ..., x^n_{im2}] \quad (23)$$

$$X_{Brood,2} = [x^1_{br2}, x^2_{br2}, ..., x^n_{br2}] \quad (24)$$

$$x^i_{br2} = \begin{cases} x^i_{im2} & \gamma_3 \leq \gamma_2 \\ x^i_{best} & \text{Otherwise} \end{cases} \quad (25)$$

where, r_1, r_2, γ_1, γ_2 and γ_3 are random numbers uniformly distributed between 0 and 1.

Between $X_{Brood,1}$ and $X_{Brood,2}$ the better one is selected as a new brood. This variant of HBMO has been named IHBMO. More explanation about this HBMO variant can be found in [17].

IV. RESULTS AND DISCUSSIONS

In order to access the capability of HBMO algorithm for solving SC-OPF problem, two test systems IEEE 30-bus-no.1 and IEEE 30-bus-no.2 are selected. More detail about these systems can be found in [11, 13]. In all the cases, bus 1 is considered as the slack bus and the limitations of bus voltage, transformer tap and compensator reactive power are set to $0.95\text{V} < V < 1.05\text{V}$, $0.91 < T < 1.05$ and $1\text{ MVAR} < QC < 20\text{ MVAR}$, respectively.

The performance of the proposed algorithm is compared with the results reported in the literature and obtained with different techniques. Due to the stochastic nature of HBMO, 50 independent runs are carried out and the minimum, mean and maximum costs of the system over these runs are reported. In HBMO algorithm, the parameter setting is N = 500, N_{sperm} = 400, N_{iter} = 30, S_{max} = 20000 and S_{min} = 10000. It is worthwhile to mention that the parameter setting is based on trial and no attempt has made to optimize it.

A. Case Study 1 - IEEE 30-Bus - No. 1

Figure 2 and Table 1 indicate the schematic diagram and information of IEEE 30-bus-no1. This system includes 6 generators, 4 tap-changing transformers and 2 capacitor banks leading to NP = 5+6+4+2=17 decision variables. For this system, the SC-OPF problem is solved in four states as follows:

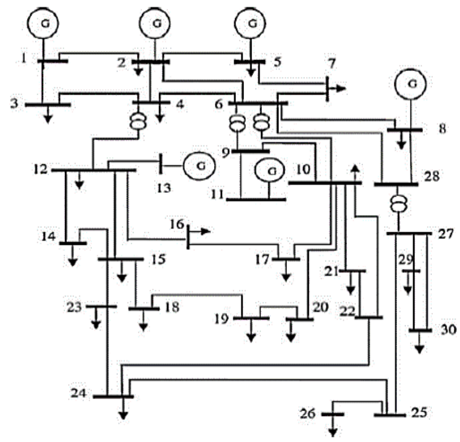

Figure 2. Schematic diagram of IEEE 30-bus - no. 1 [13]

Table.1. information of IEEE 30-bus - no. 1 [13]

Generator	1	2	3	4	5	6
a	0.00375	0.0175	0.0625	0.0083	0.025	0.025
b	2	1.75	1	3.25	3	3
c	0	0	0	0	0	0
d	18	16	14	12	13	13.5
e	0.037	0.038	0.04	0.045	0.042	0.041
P_{min}	30	20	15	10	10	12
P_{max}	250	80	50	35	30	40
Prohibited Zone	[55,66], [80-120]	[21-24], [45-55]	[30-36]	[25-30]	[25-28]	[24-30]
Bus Number	1	2	5	8	11	13

A.1. State 1 - Case Study 1 without Prohibited Operating Zones and Valve-Point Loading Effects

Table 2 lists the minimum, mean and maximum costs obtained by HBMO and IHBMO over 50 independent runs in comparison with the results found by the other techniques: IEP [18], DE-OPF [19], MDE-OPF [19], GA [20], SA [20], SGA [21], EGA [7], ACO [22], FGA [23], GA-OPF [24], EP-OPF [24], SFLA [13] and Hybrid SFLA-SA [13]. All the reported results of the other solution methods have been directly adopted from their respective references. The minimum cost of this system is 800.1639 $/h. It is clear that HBMO and IHBMO yield better results than the other methods.

Table 2. Comparison between IHBMO and other algorithms

Algorithms	Best	Worst	Average
DE-OPF	802.39	-	-
MDE-OPF	802.37	-	-
GA	804.10	805.96	805.12
SA	804.10	805.64	804.92
SGA	803.69	-	-
EGA	802.06	-	-
ACO	802.57	-	-
FGA	802.00	-	-
GA-OPF	803.91	-	-
EP-OPF	803.57	-	-
SFLA	801.97	803.46	802.31
Hybrid SFLA-SA	801.79	803.24	802.14
HBMO	801.3896	802.715	801.97
IHBMO	800.1639	800.9314	800.5112

Between HBMO and IHBMO, the latter produces more promising results than the other does. The superior performance of IHBMO will be more evident when we consider that the maximum cost function found by this algorithm is smaller than the minimum value of the other solution methods. Table 3 summarizes the best solution of this case found by IHBMO algorithm. Figure 3 illustrates the convergence process of IHBMO in comparison with HBMO. As can be seen, IHBMO finds good region of the search space at first iterations and converges to solution.

Table 3. Best solution of IHBMO algorithm for state1 of case 1

P_{G1} (MW)	P_{G2} (MW)	P_{G5} (MW)	P_{G8} (MW)	P_{G11} (MW)
184.0996	48.1366	20.4940	17.1036	10.8889
P_{G13} (MW)	V_{G1} (p.u.)	V_{G2} (p.u.)	V_{G5} (p.u.)	V_{G8} (p.u.)
12.0246	1.0450	1.0433	1.0181	1.0339
V_{G11} (p.u.)	V_{G13} (p.u.)	T_{6-9}	T_{6-10}	T_{4-12}
1.0175	1.0498	1	1	1.05
T_{27-28}	Q_{C1} (MVAR)	Q_{C2} (MVAR)	Cost ($/h)	
1.05	15	14	800.1639	

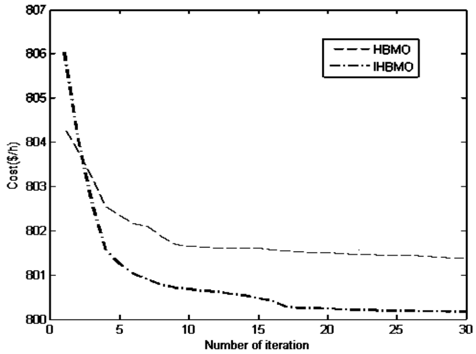

Figure 3. Convergence process of IHBMO in comparison with HBMO for state 1 of case 1

A.2. State 2 - Case Study 1 without Prohibited Operating Zones and with Valve-Point Loading Effects

Table 4 shows the performance of HBMO and IHBMO algorithms in comparison with the results found by RCGA [25], DE [25], GA [13], PSO [13], SA [13], SFLA [13] and Hybrid SFLA-SA [13]. On this case, HBMO-based algorithms outperform the other ones. The minimum cost function with the value of 820.273492 $/h belongs to IHBMO. HBMO with the minimum value of 824.929817 $/h has the second rank. The best SC-OPF solution of this case found by IHBMO algorithm is shown in Table 5. Figure 4 illustrates the convergence process of IHBMO in comparison with HBMO.

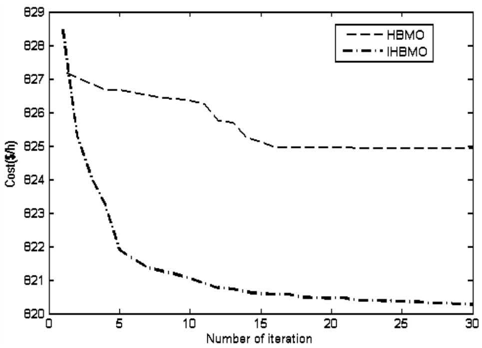

Figure 4. Convergence process of IHBMO in comparison with HBMO for state 2 of case 1

Table 4. Comparison between IHBMO and other algorithms

Algorithms	Best	Worst	Average
RCGA	831.04	-	-
DE	826.54	-	-
GA	829.4493073	-	-
PSO	826.5897702	-	-
SA	827.8262923	-	-
SFLA	825.9906126	826.924	826.573
Hybrid SFLA-SA	825.6921669	826.412	825.984
HBMO	824.929817	825.572	825.345
IHBMO	820.273492	821.642	820.8426

Table 5. Best solution of IHBMO algorithm for state2 of case 1

P_{G1} (MW)	P_{G2} (MW)	P_{G5} (MW)	P_{G8} (MW)	P_{G11} (MW)
219.7980	26.8616	15.3338	10.0079	10.0081
P_{G13} (MW)	V_{G1} (p.u.)	V_{G2} (p.u.)	V_{G5} (p.u.)	V_{G8} (p.u.)
12.007	1.0484	1.0368	1.0355	1.0443
V_{G11} (p.u.)	V_{G13} (p.u.)	T_{6-9}	T_{6-10}	T_{4-12}
1.0371	1.0497	0.99	0.98	1
T_{27-28}	Q_{C1} (MVAR)	Q_{C2} (MVAR)	Cost($/h)	
1.05	19	9	820.273492	

A.3. State 3 - Case Study 1 with Prohibited Operating Zones and without Valve-Point Loading Effects

In this state, IHBMO outperforms the other algorithms in terms of the minimum, average and maximum cost functions. Table 6 compares the performance of HBMO, IHBMO and the other solution methods reported in [13]. In this case, minimum cost function value is 800.4960901 $/h. Best SC-OPF solution found by IHBMO algorithm is shown in Table 7. Figure 5 illustrates convergence process of IHBMO in comparison with HBMO.

Table 6. Comparison between IHBMO and other algorithms

Algorithms	Best	Worst	Average
GA	809.2314784	810.48	809.83
PSO	806.4331434	808.14	807.24
SA	808.7174786	810.21	809.34
SFLA	806.2155404	807.81	806.76
Hybrid SFLA-SA	805.8152356	806.91	806.52
HBMO	801.8955031	802.6154	802.1647
IHBMO	800.4960901	801.8642	801.3487

Table 7. Best solution of IHBMO algorithm for state3 of case 1

P_{G1} (MW)	P_{G2} (MW)	P_{G5} (MW)	P_{G8} (MW)	P_{G11} (MW)
185.8423	44.9402	20.7619	17.5312	11.6797
P_{G13} (MW)	V_{G1} (p.u.)	V_{G2} (p.u.)	V_{G5} (p.u.)	V_{G8} (p.u.)
12.00784	1.0499	1.0402	1.0045	1.0240
V_{G11} (p.u.)	V_{G13} (p.u.)	T_{6-9}	T_{6-10}	T_{4-12}
1.0084	1.0475	1	1.01	1.05
T_{27-28}	Q_{C1} (MVAR)	Q_{C2} (MVAR)	Cost($/h)	
1.05	5	6	800.4960901	

A.4. State 4 - Case Study 1 with Prohibited Operating Zones and Valve-Point Loading Effects

Considering the prohibited operating zones and valve-point loading effects, the performance of IHBMO is compared with HBMO and the other algorithms [13] in Table 8. IHBMO not only produces the minimum cost function value but also its maximum cost function found is smaller than the minimum value obtained by the other algorithms. Table 9 indicates the solution and Figure 6 illustrates the convergence processes.

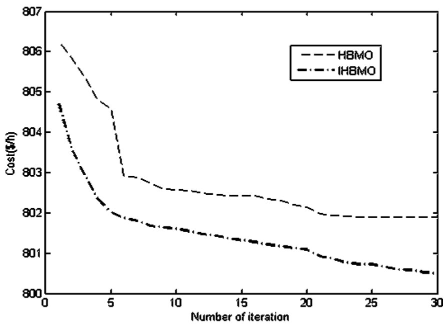

Figure 5. Convergence process of IHBMO in comparison with HBMO for state 3 of case 1

Table 8. Comparison between IHBMO and other algorithms

Algorithms	Best	Worst	Average
GA	838.1727153	-	-
PSO	835.4785807	-	-
SA	836.5364494	-	-
SFLA	834.8165531	-	-
Hybrid SFLA-SA	834.6339404	-	-
HBMO	827.4546092	829.7413	829.4312
IHBMO	821.1647333	824.6148	823.1315

Table 9. Best solution of IHBMO algorithm for state 4 of case 1

P_{G1} (MW)	P_{G2} (MW)	P_{G5} (MW)	P_{G8} (MW)	P_{G11} (MW)
219.7597	26.5523	15.7443	10.1166	10.0267
P_{G13} (MW)	V_{G1} (p.u.)	V_{G2} (p.u.)	V_{G5} (p.u.)	V_{G8} (p.u.)
12.025	1.0199	1.0091	1.0223	1.0362
V_{G11} (p.u.)	V_{G13} (p.u.)	$T_{6\text{-}9}$	$T_{6\text{-}10}$	$T_{4\text{-}12}$
1.0181	1.0450	0.96	0.94	1
$T_{27\text{-}28}$	Q_{C1} (MVAR)	Q_{C2} (MVAR)	Cost($/h)	
1.02	11	11	821.1647333	

B. Case Study 2 - IEEE 30-Bus - No. 2

The schematic diagram of IEEE 30-bus - no. 2 is depicted in Figure 7 and Table 10 gives the related information. In this case, study, both prohibited operating zones and valve-point loading effects are taken into consideration. This system includes 6 generators, 4 tap-changing transformers and 2 capacitor banks leading to NP = 5+6+4+2 = 17 decision variables.

Table 10. Information of IEEE 30-bus - no. 2 [26]

Generator	1	2	3	4	5	6
a	0.00375	0.0175	0.0625	0.0083	0.025	0.025
b	2	1.75	1	3.25	3	3
c	0	0	0	0	0	0
d	18	16	14	12	13	13.5
e	0.037	0.038	0.04	0.045	0.042	0.041
$P_{\min}$	30	20	15	10	10	12
$P_{\max}$	250	80	50	55	30	40
Prohibited Zone	[55,66], [80-120]	[21-24], [45-55]	[30-36]	[25-30]	[25-28]	[24-30]
Bus Number	1	2	22	27	23	13

Table 11 shows the comparison of the results obtained by HBMO, IHBMO and those found by PSO [1], HPSO [1], RDEA [26] and IBF [11]. As can be seen, IHBMO produces the most promising results in comparison with the other methods. For this system, minimum cost function value is 501.019908 $/h. Table 12 shows optimal solution and Figure 8 illustrates the convergence processes.

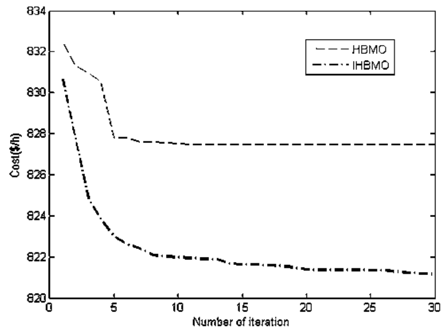

Figure 6. Convergence process of IHBMO in comparison with HBMO for state 4 of case 1

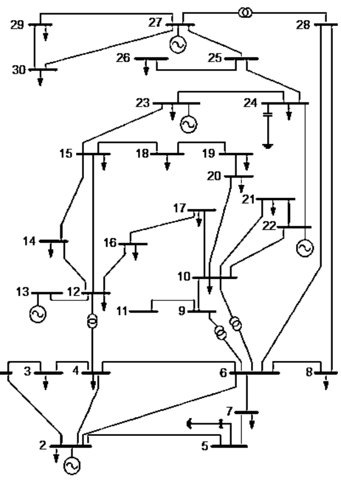

Figure 7. Schematic diagram of IEEE 30-bus - no. 2 [26]

Table 11. Comparison between IHBMO and other algorithms

Algorithms	Best	Worst	Average
PSO	635.269	-	-
HPSO	615.250	-	-
RDEA	582.843	-	-
IBF	577.666	-	-
HBMO	545.3019917	556.2145	552.8627
IHBMO	501.019908	520.8562	514.9753

Table 12. Best solution of IHBMO algorithm for case 2

P_{G1} (MW)	P_{G2} (MW)	P_{G22} (MW)	P_{G27} (MW)	P_{G23} (MW)
120.4218	26.4101	15.1209	10.6591	10.5752
P_{G13} (MW)	V_{G1} (p.u.)	V_{G2} (p.u.)	V_{G22} (p.u.)	V_{G27} (p.u.)
12.0027	1.0094	0.9696	0.9766	0.9545
V_{G23} (p.u.)	V_{G13} (p.u.)	$T_{6\text{-}9}$	$T_{6\text{-}10}$	$T_{4\text{-}12}$
0.9589	0.9842	0.98	0.98	1.02
$T_{27\text{-}28}$	Q_{C1} (MVAR)	Q_{C2} (MVAR)	Cost($/h)	
1.03	8	11	501.019908	

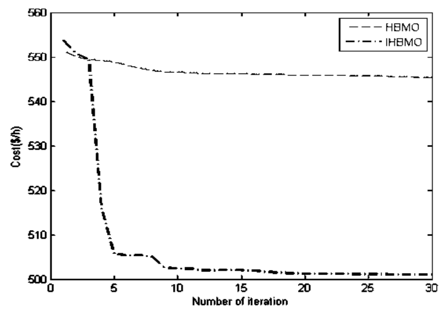

Figure 8. Convergence process of IHBMO in comparison with HBMO for case 2

V. CONCLUSIONS

In this paper, original HBMO and an improved version of this algorithm (IHBMO) are used to solve the SC-OPF problem considering prohibited operating zones and valve-point loading effects. The performance of this algorithm is evaluated on two test systems and also compared with the other techniques. Simulation results are quite promising and reveal that IHBMO has the best performance and best speed of convergence in comparison with HBMO and the other studied algorithms. It is concluded that IHBMO can be an efficient and a powerful candidate to solve the SC-OPF problem and other optimization problems with different constraints and objective functions.

REFERENCES

[1] M.R. Al-Rashidi, 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, pp. 2030-2038, 2007.

[2] D.I. Sun, B. Ashley, B. Brewer, A. Hughes, W.F. Tinney, "Optimal Power Flow by Newton Approach", IEEE Trans. Power Appar. System, Vol. 103, pp. 2864-2875, 1984.

[3] A. Al-Muhawesh Tareq, S. Qamber Isa, "The Established Megawatt Linear Programming-Based Optimal Power Flow Model Applied to the Real Power 56-Bus System in Eastern Province of Saudi Arabia", International Journal of Energy, Vol. 33, pp. 12-21, 2008.

[4] H. Habiabollahzadeh, L. Luo, A. Semlyen, "Hydrothermal Optimal Power Flow Based on Combined Linear and Nonlinear Programming Methodology", IEEE Trans. Power Appar. System, Vol. 4, pp. 530-537, 1989.

[5] R.C. Burchet, H.H. Happ, D.R. Vierath, "Quadratically Convergent Optimal Power Flow", IEEE Trans. Power Appar. System, Vol. 103, pp. 3267-3276, 1984.

[6] X. Yan, V.H. Quintana, "Improving an Interior Point Based OPF by Dynamic Adjustments of Step Sizes and Tolerances", IEEE Trans. Power System, Vol. 14, pp. 709-717, 1999.

[7] A.G. Bakirtzis, P.N. Biskas, C.E. Zoumas, V. Petridis, "Optimal Power Flow by Enhanced Genetic Algorithm", IEEE Trans. Power System, Vol. 17, pp. 229-236, 2002.

[8] M.A. Abido, "Optimal Power Flow Using Particle Swarm Optimization", Electric Power Energy System, Vol. 24, pp. 563-571, 2002.

[9] M. Varadarajan, K.S. Swarup, "Network Loss Minimization with Voltage Security Using Differential Evolution", Electric Power System Research, Vol. 78, pp. 815-823, 2008.

[10] M.A. Abido, "Optimal Power Flow Using Tabu Search Algorithm", Electric Power Components System, Vol. 30, pp. 469-483, 2002.

[11] N. Amjady, H. Fatemi, H. Zareipour. "Solution of Optimal Power Flow Subject to Security Constraints by a New Improved Bacterial Foraging Method", IEEE PES Trans. Power System, Vol. 20, 2011.

[12] C.A. Roa Sepulveda, B.J. Pavez Lazo, "A Solution to the Optimal Power Flow Using Simulated Annealing", Electrical Power Energy System, Vol. 25, pp. 47-57, 2003.

[13] T. Niknam, M.R. Narimani, R.A. Abarghooee, "A New Hybrid Algorithm for Optimal Power Flow Considering Prohibited Zones and Valve Point Effect", Energy Convers. Manage, Vol. 58, pp. 197-206, 2012.

[14] A. Afshar, O.B. Haddad, M.A. Marino, B.J. Adams, "Honey-Bee Mating Optimization (HBMO) Algorithm for Optimal Reservoir Operation", J. Franklin Inst., Vol. 344, pp. 452-462, 2007.

[15] H.A. Shayanfar, E.S. Barazandeh, S.J.S. Shenava, A. Ghasemi, O. Abedinia, "Solving Optimal Unit Commitment by Improved Honey Bee Mating Optimization", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 13, Vol. 4, No. 4, pp. 38-45, December 2012.

[16] A. Karimi, H. Eskandari, M. Sedighizadeh, A. Rezazadeh, A. Pirayesh, "Optimal PID Controller Design for AVR System Using New Optimization Algorithm", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 15, Vol. 5, No. 2, pp. 123-128, June 2013.

[17] T. Niknam, H.Z. Meymand, H.D. Mojjarad, "An Efficient Algorithm for Multi-Objective Optimal Operation Management of Distribution Network Considering Fuel Cell Power Plants", Energy, Vol. 36, pp. 119-132, 2011.

[18] W. Ongsakul, T. Tantimaporn, "Optimal Power Flow by Improved Evolutionary Programming", Electric Power Component System, Vol. 34, pp. 79-95, 2006.

[19] S. Sayah, K. Zehar, "Modified Differential Evolution Algorithm for Optimal Power Flow with Non-Smooth Cost Functions", Energy Convers. Manage, Vol. 49, pp. 3036-3042, 2008.

[20] W. Ongsakul, P. Bhasaputra, "Optimal Power Flow with FACTS Devices by Hybrid TS/SA Approach", International Journal Electric Power Energy System, Vol. 24, pp. 851-857, 2002.

[21] T. Bouktir, L. Slimani, B. Mahdad, "Optimal Power Dispatch for Large-Scale Power System Using Stochastic Search Algorithms", International Journal Power Energy System, Vol. 28, pp. 1-10, 2008.

[22] L. Slimani, T. Bouktir, "Economic Power Dispatch of Power System with Pollution Control Using Multi Objective Ant Colony Optimization", International Journal Computation Intelligence Research, Vol. 3, pp. 145-153, 2007.

[23] A. Saini, D.K. Chaturvedi, A.K. Saxena, "Optimal Power Flow Solution - A GA-Fuzzy System Approach", International Journal Emergency Electric Power System, Vol. 5, pp. 1-21, 2006.

[24] Y.R. Sood, "Evolutionary Programming Based Optimal Power Flow and its Validation for Deregulated Power System Analysis", International Journal Electric Power Energy System, Vol. 29, pp. 65-75, 2007.

[25] M. Basu, "Multi-Objective Optimal Power Flow with FACTS Devices", Energy Convers. Manage, Vol. 52, pp. 903-910, 2011.

[26] N. Amjady, H. Sharifzadeh, "Security Constrained Optimal Power Flow Considering Detailed Generator Model by a New Robust Differential Evolution Algorithm", Electric Power System Research, Vol. 81, 2011.

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