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A Hybrid Particle Swarm Optimization and Gravitational Search Algorithm for Solving Optimal Power Flow Problem

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Abstract

The gravitational search algorithm is one of the new heuristic search optimization methods which are based on gravity law. Despite having high capability, this approach suffers from low search speed duo to lack of memory. To overcome this problem, the particle swarm optimization method has been used. Therefore, in this paper, hybrid particle swarm optimization and gravitational search algorithm has been used to find the solution of optimal power flow. Performance of the proposed method has been evaluated using different objective functions on the IEEE 30-bus and 57-bus test systems. Comparing the results of this method with other methods shows better performance of the proposed method.

Keywords: Optimal power flow, Hybrid particle swarm optimization and gravitational search algorithm, Cost function.

1.INTRODUCTION

Optimal power flow, due to its importance in planning and operation of power systems, has been in the focus of wide attention in the recent years. The purpose of optimal power flow is to find the optimal value of control variables of a power system in such way that the minimum of the value of the specified objective function is obtained and equality and inequality constraints have also been satisfied. Objective functions which have been used in optimal power flow include wide kinds. Among those, the objective function of the fuel cost is one of the most applicable objective functions, which has been used. Equality constraints include equations of power flow and inequality constraints include the equipment operation constrains and security constraints of the system.

For the first time, optimal power flow was introduced in the late 1960s [1]. Since that time, several researchers have reviewed this problem and have researched about it. Initially, methods which were introduced for solving the optimal power flow problem were classical methods. Gradient method [2], nonlinear programming [3 and 4], linear programming [5], quadratic programming [6], Newton method [7], and the interior point method [8 – 10] were classical methods which were used for solving the optimal power flow problem. But these methods can't find a proper optimal solution in problems which have nonlinear and continuous – discrete constraints and objective functions. Thus, to overcome this problem, wide kinds of the heuristic methods has been used for solving the optimal power flow problem. Among these methods, we can refer to genetic algorithm [11, 12], simulated annealing [13], differential evolution algorithm [14, 15], evolutionary programming [16, 17], particle swarm optimization [18, 19], and gravitational search algorithm [20].

Despite the advantages that the heuristic method has, each of them has their own particular disadvantages. One of the methods of overcoming these advantages is a combination of these

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algorithms. Recently, several hybrid algorithms such as the hybrid differential evolution algorithm [21], hybrid simulated annealing – genetic algorithm [22], hybrid genetic algorithm – differential evolution [23] have been recommended for solving the optimization problems.

Gravitational search algorithm is a new heuristic search algorithm which in the recent years has been widely used for solving the optimization problem due to its high searching capability. Nevertheless, this method has low searching speed since it lacks memory of past data. Thus, in a similar number of repetitions, it doesn't find an optimal solution in comparison with other methods. To overcome this problem, the particle swarm optimization method, which has memory, has been used. Thus, in this article, a hybrid particle swarm optimization and gravitational search algorithm (which in the following we call it hybrid gravitational search algorithm for simplicity) is used for solving the optimal power flow problem.

The rest of the article is divided to four sections: section 2 shows the formulation of the optimal power flow problem. In section 3, the structure of the gravitational search algorithm and the hybrid gravitational search algorithm has been expressed. In section 4, the results of solving the optimal power flow using the proposed method and comparison with other methods have been provided with IEEE 30-bus and 57-bus test systems. In section 5, a conclusion of the application of the recommended method has also been provided.

2. FORMULATION OF THE PROBLEM

The purpose of solving the optimal power flow problem is to find an optimal value of the control variables which provides the minimum value of the objective function and simultaneously, it satisfies the equality and inequality constrains. Generally, an optimal power flow problem is formulated as follows:

(1) $\min \quad f(x,u)$

(2) $$subject \quad to: \begin{cases} g(x,u)=0 \\ h(x,u)\le 0 \end{cases}$$

F shows the objective function, g equality constraints and h inequality constraints. The vector of control and dependent variables has been respectively shown with u and x.

Active power of slack bus PG1, voltage of the load buses VL, reactive power of generators QG and transmission line loading SL are the vector of dependent variables.

(3) $$x=[P_{G_1},V_{L_1},...,V_{L_{NPQ}},Q_{G_1},...,Q_{G_{NG}},S_{L_1},...,S_{L_{NL}}]$$

In 3, NPQ, NG and NL are the number of bus loads, number of generation buses and the number of transmission lines, respectively.

Vector of control variables include active power of generation buses PG except at the slack bus PG1, voltage of generators VG, Shunt VAR compensator QC and settings of tap transformers T.

(4) $$u=[P_{G_2},...,P_{G_{NG}},V_{G_1},...,V_{G_{NG}},Q_{C_1},...,Q_{C_{NC}},T_1,...,T_{NT}]$$

In 4, NC and NT are number of shunt VAR compensators and tap regulating transformers, respectively.

2.1. Constraints

2.1.1. Equality constraints

g or equality constraints is the power flow equations which are defined as follows:

(5) $$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)) = 0$$

(6) $$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j (G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)) = 0$$

In these equations, Vi and Vj are voltage of i and j buses, respectively, N is the number of buses, PGi and QGi are active and reactive power generation, PDi and QDi are the active and reactive load demands. Gij and Bij and δij are the inductance, susceptance and phase difference of voltages between bus i and bus j.

2.1.2. Inequal constraints

h or inequality constraints include the following items:

a) constraints associated with generation: voltage of generation buses, output of active and reactive powers are limited as follows through their high and low limits:

(7) $$\begin{aligned} &V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \\ &P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \\ &Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i = 1,\ldots,NG \end{aligned}$$

In 7, VGimin and VGimax are the minimum and maximum voltages of the generation unit i. PGimin and PGimax are the minimum and maximum of the active power of ith generation unit and QGimin and QGimax are the minimum and maximum of the reactive power of ith generation unit.

b) Transformers constraints: transformer tap settings are limited as follows through their high and low limits:

(8) $$T_i^{\min} \le T_i \le T_i^{\max} \qquad i = 1,\ldots,NT$$

Timin and Timax are the minimum and maximum tap setting of the ith transformer.

c) Shunt VAR compensator constraints: Shunt VAR compensator are limited through their limitations as follows:

(9) $$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max} \qquad i = 1,\ldots,NC$$

Qcimin and Qcimax are the minimum and maximum of the injection of the ith Shunt VAR compensator.

d) Security limitations: they include the voltage of load buses and loading of transmission lines as follows:

(10) $$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} \qquad i = 1,\ldots,NPQ$$

(11) $$S_{li} \le S_{li}^{\max} \qquad i = 1,\ldots,NTL$$

VLimin and VLimax are the minimum and maximum of the voltage of load bus i. Sli is the apparent power flow of the ith line and Slimax is the maximum of the apparent power flow of the ith line.

The dependent variables are limited by considering them in the objective function as quadratic penalty terms. Thus the objective function changes as follows:

(12)
$$J=\sum_{i=1}^{NG}F_i(P_{Gi})+\lambda_p(P_{G1}-P_{G1}^{\lim})^2+\lambda_v\sum_{i=1}^{NPQ}(V_{Li}-V_{Li}^{\lim})^2$$
$$+\lambda_Q\sum_{i=1}^{NG}(Q_{Gi}-Q_{Gi}^{\lim})^2+\lambda_S\sum_{i=1}^{NTL}(S_{li}-S_{li}^{\lim})^2$$

In which, λP, λV, λQ and λs are the penalty factors. Xlim is the limit value of the dependent variable x which is defined as follows:

(13)
$$x^{\lim}=\begin{cases}x & x^{\min}\le x\le x^{\max}\\ x^{\max} & x>x^{\max}\\ x^{\min} & x<x^{\min}\end{cases}$$

3. HYBRID GRAVITATIONAL SEARCH ALGORITHM

3.1. A brief introduction of gravitational search algorithm

Gravitational search algorithm is a new stochastic search method in which agents are objects that their performances are measured based on their masses and all of these objects attract each other with gravity force; whereas this force leads to the overall movement of all objects towards objects with heavier masses [20, 24].

Assume there are N agents (masses), the position of ith agent is Xi = (Xi1,…, Xid,…, Xin) for i = 1,…,N.

In which, n is the dimension of problem space and Xid is the position of ith agent in the dth dimension.

According to Newton's gravity low, the force on the ith mass from jth mass is defined as follows:

(14)
$$F_{ij}^d(t)=G(t)\frac{M_i(t)\times M_j(t)}{\left\|X_i(t),X_j(t)\right\|_2}(x_i^d(t)-x_j^d(t))$$

Mi and Mj are the masses of the agents, G(t) is the gravitational constant at the time t. Mi is obtained from , and as a result, , fiti(t) is the value of objective function for that agent and best and worst are the best and the worst values of the objective function of all agents, respectively.
For the ith agent, the total of the force exerted from the other agents is defined as follows:

(15)
$$F_i^d(t)=\sum_{j\neq i}rand_jF_{ij}^d(t)$$

In which, randi is a random number in the range [0 and 1], according to the law of motion, acceleration of the ith agent is calculated as follows:

(16) $$a_i^d(t) = \frac{F_i^d(t)}{M_i(t)}$$

Thus, the strategy of searching based on this concept is described through the equations below:

(17) $$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t)$$

(18) $$x_i^d(t+1) = x_i^d(t) + v_i^d(t)$$

In the equation above, Xid is the position of ith agent in the dth dimension and Vid is velocity and aid is the acceleration.
Gravitational constant G(t) is defined as a function of time as follows:

(19) $$G(t) = G_0 \exp(-\beta.\frac{t}{\max - t})$$

In which, G0 is the initial value, β is a constant, t is the number of current iterations and max-t is the maximum of iterations.

3.2. Hybrid gravitational search algorithm

Gravitational search algorithm, despite algorithms based on the simulation of animals' social behavior, is an optimization algorithm which has been inspired by the law of gravity. Particle swarm optimizing algorithm is a known stochastic search algorithm which has been used in solving several problems of optimization.

In both gravitational search algorithm and particle swarm optimization algorithm, the optimal value is obtained with the motion of the agent in the searching space, but the strategies of the movement are different. In the gravitational search algorithm, the movement of the agent is calculated based on the total force exerted from the other agents. Gravitational search algorithm is a method that lacks memory and only the current position of the agent plays a role in the process of updating the agent's position. Particle swarm optimization uses a kind of memory (best previous position of each individual) and group information among individuals (best previous position obtained among all individuals); thus the speed of the movement of the individuals increases towards the optimal solution.

The searching strategy of particle swarm optimization, it is described in [18], is as follows:

(20) $$\begin{aligned} v_i^d(t+1) = {} & v_i^d(t) + c_1 rand_{i1}(pbest_i^d(t) - x_i^d(t)) \\ & + c_2 rand_{i2}(gbest^d(t) - x_i^d(t)) \end{aligned}$$

(21) $$x_i^d(t+1) = x_i^d(t) + v_i^d(t)$$

In which c1 and c1 are positive constants, pbesti is the best previous position of ith particle and gbest is the best previous position of all particles.

In this article, in order to improve the performance of gravitational search algorithm, the idea of memory and group information of particle swarm optimization has been used. Hybrid gravitational search algorithm is a new movement strategy in the searching space by implementing the law of gravity and being guided by memory and group information.

Equation of updating the velocity of the hybrid gravitational search algorithm is defined as follows:

(22) $$v_i^d(t+1) = rand_{i1} \times v_i^d(t) + a_i^d(t) \quad + c_1 rand_{i2}(pbest_i^d(t) - x_i^d(t)) \quad + c_2 rand_{i3}(gbest^d(t) - x_i^d(t))$$

In which, c1 and c1 are the values of positive constants in the range [0 and 1]. By adjusting the values of c1 and c1, we can balance the impact of gravity law and impact of memory and group information. Demonstration of the flow chart of this algorithm has been shown in figure 1.

In this article, the hybrid gravitational search algorithm has been used for solving the optimal power flow and the improvement of its performance has been shown through experimantal results.

3.3. Application of hybrid gravitational search algorithm for the optimal power flow problem

In this section, the application of hybrid gravitational search algorithm is described for solving the optimal power flow problem:

Step 1: defining the searching space.
Step 2: generation of initial population between the minimum and maximum values of control variables which is considered as the position of agents.
Step 3: calculation of the value of fitness function of each agent for the optimal power flow problem.
Step 4: updating G(t), best(t), worst(t), gbest, pbesti and Mi(t) for i = 1,…,N.
Step 5: calculation of total forces in different directions.
Step 6: calculation of acceleration and velocity.
Step 7: updating the position of agent.
Step 8: repeating steps 3-7 until reaching the stopping criterion.
Step 9: stopp.

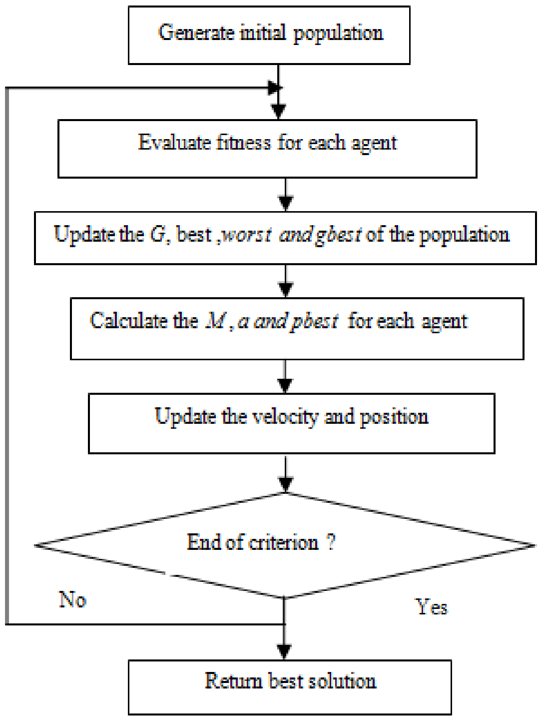

Figure 1. The flow chart of hybrid gravitational search algorithm.

4. RESULTS OF SIMULATION

4.1. IEEE 30-bus test system

In this section, the results obtained from simulation of hybrid gravitational search algorithm for solving the optimal power flow problem has been shown. In order to evaluate the performance, recommended method has been experimented on a 30-bus test system. Data associated with generators, buses, lines and minimum and maximum of the value of control variables has been provided in [20].

30-bus test system has 6 generators in buses 1, 2, 5, 8, 11 and 13 and also 4 transformers in lines 6-9, 6-10, 4-12 and 27-28. Shunt VAR compensators are also in buses 10, 12, 15, 17, 20, 21, 23, 24 and 29. These compensators has only been used in the first case and in the second to fourth one, in order for the comparison to be fair, they haven't been used. Total demand of the system is 2.834 p.u. at 100 MVA base. Maximum and minimum of the voltage of all load buses has been considered to be 0.95 – 1.05. The recommended method for solving the optimal power flow problem has been used in various cases with different objective functions. Values of the parameters used in the hybrid gravitational search algorithm in simulation have been provided in table 1.

Table 1. Parameters of hybrid gravitational search algorithm.

Parameters	value	Parameters	value
Number of the population	50	c_2	0.5
Number of the implementation of the algorithm	20	G_0	1
Number of iterations	100	β	1
c_1	0.5	Penalty coefficients	1000

The recommended algorithm has been implemented in the environment of MATLAB and simulation has been implemented in a Pentium computer IV with a 2 GB memory. The results of simulation have been provided in the following section:

4.1.1. First case: fuel cost function

The objective function of this case is finding the minimum fuel cost of all generators which is defined as follows:

$$J = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \tag{23}$$

In which, Fi and PGi are respectively the fuel cost and the output of the active power of the ith generator. ai, bi and ci are the cost coefficients of ith generator and NG is the number of all generators. The value of these coefficients has been provided in [20]. The optimal settings of the control variables which have been obtained from the hybrid gravitational search algorithm have been provided in table 2. The minimum, mean and maximum costs obtained from the hybrid search algorithm have been obtained to be 799.99, 461, 800 and 801.2784 \$/h. Figure 2 shows the convergence curve associated with the minimum of the total fuel cost obtained from the recommended method. In order to evaluate the efficiency of the recommended method, a comparison between the results obtained from the recommended algorithm and the obtained results in various papers have been provided in table 3.

By comparing the values of the table 3, we can find out that not only the recommended method is better than other methods in finding the minimum cost, but it also functions better than other methods in the mean and maximum of the obtained cost.

Table 2. Best settings of control variables for various test cases in 30-bus test system.

Settings of the control variable in per unit	First case	Second case	Third case	Fourth case
P_1	1.7756	1.944	1.3999	1.796
P_2	0.4865	0.5206	0.5499	0.45
P_5	0.2137	0.1562	0.2434	0.2224
P_8	0.2067	0.10	0.3279	0.2139
P_{11}	0.1198	0.10	0.1814	0.1222
P_{13}	0.12	0.10	0.2015	0.1204
V_1	1.0984	0.12	1.0938	1.0964
V_2	1.0785	1.0997	1.0749	1.0765
V_5	1.0471	1.0774	1.0401	1.0455
V_8	1.0513	1.04	1.048	1.0513
V_{11}	1.0364	1.0457	1.0508	1.01
V_{13}	1.0397	1.0842	1.0444	1.0578
T_{6-9}	1.0044	1.079	1.0076	0.989
T_{6-10}	1.0425	0.9927	0.9093	1.0259
T_{4-12}	0.9889	0.9429	1.0440	1.0159
T_{28-27}	0.9902	0.9606	1.0290	1.0016
Q_{10}	0.1018	-	-	-
Q_{12}	0.1353	-	-	-
Q_{15}	0.0163	-	-	-
Q_{17}	0.067	-	-	-
Q_{20}	0.0609	-	-	-
Q_{21}	0.111	-	-	-
Q_{23}	0.0257	-	-	-
Q_{24}	0.0804	-	-	-
Q_{29}	0.0266	-	-	-
Cost ($/h)	799.99	918.4163	648.072	801.1210
Loss (MW)	8.83	10.68	7.00	9.09

Table 3. Comparison the obtained results for 1st case of the 30-bus test system.

Method	Fuel cost($/h)		
	min	mean	max
HGSA	799.99	800.461	801.2784
GSA [25]	805.1752	812.1935	827.459
PSO [18]	800.41	-	-
ABC [25]	800.66	800.8715	801.8674
MICA-TLA [26]	801.0488	-	-
MSFLA [27]	802.287	802.4138	802.5087
MDE [28]	802.376	802.382	802.404
EGA [29]	802.04	-	-
Gradient [1] Method	804.853	-	-

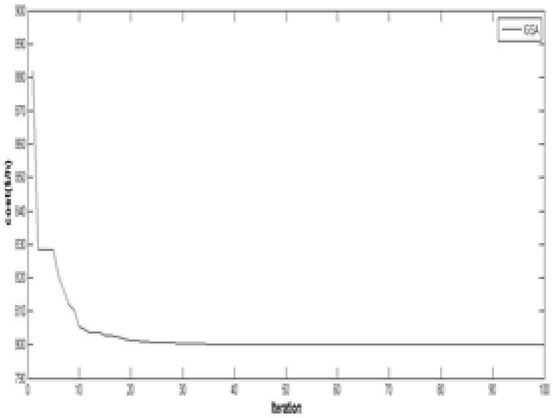

Figure 2. Algorithm convergence for the first case.

4.1.2. Second case: fuel cost function with valve point loading

In the second case, we include the impact of loading on the performance of the generation units, in such way that a sine component is added to the cost curve of the generators and we want to simulate the impact of vale point loading on their characteristic. In this case, the impact of valve point loading in the units located in buses 1 and 2 are considered. Cost coefficients for these units have been provided in [20].
Objective function can be described as follows:

$$J = \sum_{i=1}^{2} a_i + b_i P_{Gi} + c_i P_{Gi}^2 + \left| d_i \sin(e_i (P_{Gi}^{\min} - P_{Gi})) \right| + \sum_{i=3}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \qquad (24)$$

In which, ai, bi, ci, di, and ei are the cost coefficient of ith generator. Figure 3 shows the algorithm convergence for this case.

The obtained optimal settings for the control variables which have been obtained by the recommended method have been provided in table 2 and the recommended method and the methods mentioned in various papers have been compared in table 4. The cost obtained by this method is 918.4163 $/h which is less than the results obtained from other algorithms.

Table 4. Comparison of the obtained results for the second case of 30-bus test system.

Method	Fuel cost($/h)		
	min	mean	max
HGSA	918.4163	922.8461	938.8714
ABC [25]	945.4495	960.5647	973.5995
MDE [28]	930.793	942.501	954.073

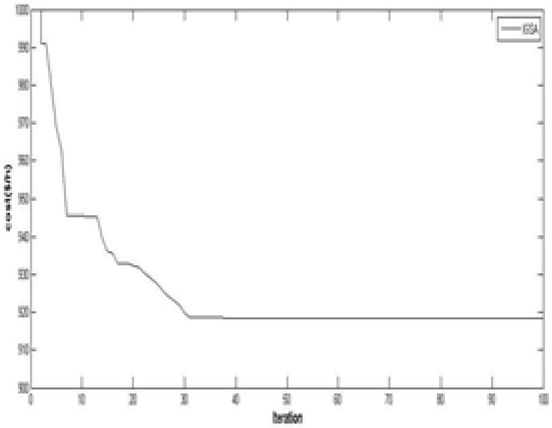

Figure 3. Algorithm convergence for the second case.

4.1.3. Third case: piecewise quadratic cost curve

From a practical perspective, in a power system, many thermal generation units might work with several types of fuel such as oil, coal or natural gas. Fuel cost function of these units might be a piecewise quadratic fuel cost function for several types of fuel.

In this paper, the fuel cost function for generation units in buses 1 and 2 are shown as a piecewise quadratic function so that it would model several fuels. The function of these units is written as follows:

$$F(P_{Gi}) = \begin{cases} a_{i1} + b_{i1}P_{Gi} + c_{i1}P_{Gi}^2 & P_{Gi}^{\min} \le P_{Gi} \le P_{Gi1} \\ a_{i2} + b_{i2}P_{Gi} + c_{i2}P_{Gi}^2 & P_{Gi1} \le P_{Gi} \le P_{Gi2} \\ \dots & \\ a_{ik} + b_{ik}P_{Gi} + c_{ik}P_{Gi}^2 & P_{Gi(k-1)} \le P_{Gi} \le P_{Gi}^{\max} \end{cases} \quad (25)$$

In which, aik, bik, and cik are the coefficients of the ith generation unit cost for the fuel type k. These coefficients have been provided for the generation units located in buses 1 and 2 in [20]. Coefficients of other units are similar to the first case and therefore, the objective function is written as follows:

$$J = \sum_{i=1}^{2} a_{ik} + b_{ik}P_{Gi} + c_{ik}P_{Gi}^2 + \sum_{i=3}^{NG} a_i + b_iP_{Gi} + c_iP_{Gi}^2 \quad (26)$$

Table 2 shows the results obtained from optimization for the best solution and table 5 shows a comparison between the results obtained from the recommended method and reported methods in various papers show that clearly the recommended method has better results. The convergence curve of the recommended method has also been provided in figure 4.

Table 5. Comparison of the obtained results for the third case of 30-bus test system.

Method	Fuel cost($/h)		
	min	mean	max
HGSA	648.072	652.2949	657.8530
ABC [25]	649.0855	654.0784	659.7708
DE [28]	650.8224	-	-

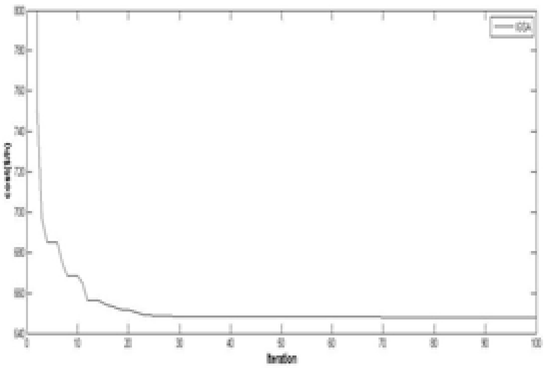

Figure 4. Algorithm convergence for the third case.

4.1.4. Fourth case: fuel cost function by considering the prohibited zones

Prohibited operating zones in the units strongly limit the ability of the unit in adjusting the load of the system, because load adjustment might lead the unit to be in its Prohibited operating zones. Thus, at the time of adjusting the output of a unit, working in Prohibited zones shall be prevented. Additional conditions for units with Prohibited zones are shown as follows:

$$\begin{aligned} & P_{Gi}^{\min} \le P_{Gi} \le P_{Gi1}^{l} \\ & P_{Gij-1}^{u} \le P_{Gi} \le P_{Gi1}^{l} \qquad j = 2,3,\dots,m_i \\ & P_{Gimi}^{u} \le P_{Gi} \le P_{Gi}^{\max} \end{aligned} \tag{27}$$

In which mi is the number of Prohibited zones in the ith unit, i and u also specify the high and low limit of Prohibited zones of the generator.

Cost coefficients and limits of the Prohibited zones for each six units have been provided in [30]. Algorithm convergence curve has been shown in figure 5 and the optimal adjustments for control variables which have been obtained for this case have been shown in table 2. A comparison between the results obtained from the recommended method and other methods have been provided in table 6 which shows the better perforemance of the recommended method.

Table 6. Comparison of the obtained results for the fourth case of 30-bus test system.

Method	**Fuel cost($/h)**		
	min	mean	max
HGSA	801.1210	80.8868	817.3247
MICA-TLA [26]	801.3302	-	-
SFLA-SA [30]	805.8152	-	-

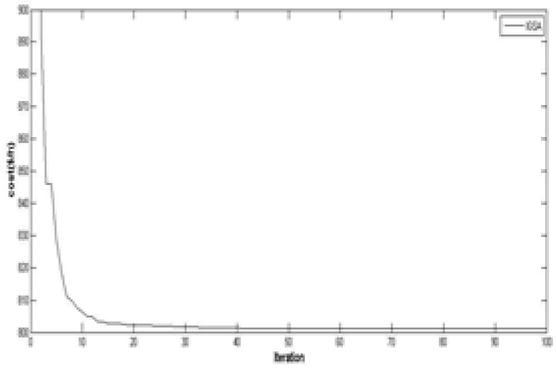

Figure 5. Algorithm convergence for the fourth case.

4.2. IEEE 57-bus test system

In order to evaluate the impact and performance of the hybrid gravitational search algorithm in power systems with larger scale, a 57-bus system has been considered. The 57-bus system include 7 generators in buses 1, 2, 3, 6, 8, 7 and 12 and also 80 transmission lines and 15 lines 3, under load tap setting transformer. Shunt VAR compensators in buses 18, 25 and 53 have been considered and the total load demand of the system are 1250.8 MW and 336.4 MVAR. Data associated with buses, lines and cost coefficient and minimum and maximum generation of active power has been provided in [31]. The maximum and minimum values of the voltage of all buses have been adjusted in 0.94 – 1.06 p.u. Tap setting transformers control variables are considered in 0.9 – 1.1 p.u. and the minimum and maximum value of the shunt VAR compensators sources are considered in 0 – 0.3 p.u.

The objective function which is used here in order to evaluate the performance of the recommended method is finding the minimum value of the quadratic fuel cost function which is written as follows:

(28) $$J = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NG} a_i + b_i P_{Gi} + c_i P_{Gi}^2$$

In which Fi and PGi are the fuel cost of the ith generator and the active power output of the ith generator, respectively. ai, bi and ci are the cost coefficients of the ith generator and NG is the number of all generators.

The results which have been obtained from the simulation for the control variable have been provided in table 7. Figure 6 shows the curve of the convergence of the best fuel cost which has been obtained from the recommended method. Table 8 also shows a comparison of the costs obtained from the recommended algorithm and the results obtained from other method and by comparing the values we can understand that the recommended method achieves better numbers.

Table 7. Best adjustments of control variables in the 57-bus test system.

Control variables (p.u.)		Control variables (p.u.)	
P1	1.4559	T24-25	0.9276
P2	0.6905	T24-25	1.0243
P3	0.4756	T24-26	0.9604
P6	0.8584	T7-29	0.9496
P8	4.6175	T34-32	1.0233
P9	0.7989	T11-41	0.9826
P12	3.7666	T15-45	1.0052
V1	1.0292	T14-46	0.9671
V2	1.0272	T10-51	0.9756
V3	1.0175	T13-49	0.9647
V6	1.0378	T11-43	0.9585
V8	1.0437	T40-56	1.0010
V9	1.0181	T39-57	1.0415
V12	1.0142	T9-55	0.9472
T4-18	0.9925	Q18	0.0858
T4-18	1.0568	Q25	0.1719
T21-20	0.9753	Q53	0.0924
Fuel cost ($/h)		41732.8626	
Losses (MW)		15.54	

Table 8. Comparison of the obtained results for the 57-bus test system.

Method	Fuel cost ($/h)
HGSA	41732.8626
GSA [25]	5289.7052
LDI-PSO [25]	41815.5035
BASE-CASE [32]	51347.86
MATPOWER [32]	41737.79

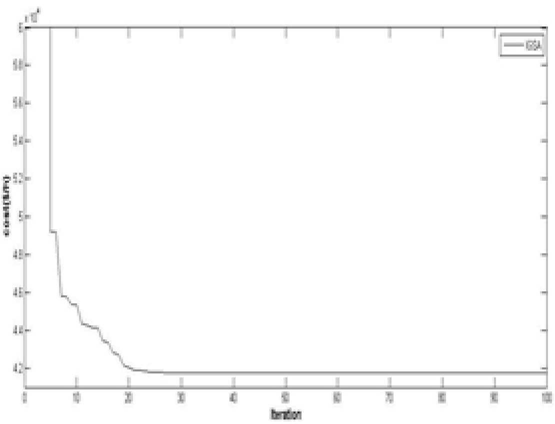

Figure 6. Algorithm convergence for the 57-bus test system.

5. CONCLUSION

In this paper, the hybrid gravitational search algorithm has been recommended as a new method for solving the optimal power flow problem. Initially, the optimal power flow problem was described as a nonlinear optimization problem with equality and inequality constraints in the power systems. Throughout the study, several cost functions such as the quadratic objective function, cost function with the valve point loading, piecewise quadratic cost function and cost function by considering the prohibited zones.

As the results of simulation showed, the recommended algorithm was successfully able to achieve the best global or near global best settings of control variables in a 30-bus and 57-bus test system. The evaluate and comparison of the results obtained from the application of this method with other methods showed that this method provides better results which show this characteristic of the hybrid gravitational search algorithm that this method is less likely to find local optimums.

REFERENCES

[1] Dommel,H.W., Tinney,T.F., “Optimal power flow solutions”, IEEE Transactions on Power Apparatus System, Vol.87, No.5, pp. 1866–1876, 1968.
[2] Minano, RZ., Van Cutsem, T., Milano, F., Conejo, AJ., “Securing transient stability using time-domain simulations within an optimal power flow”, IEEE Transactions on Power System, Vol.25, No.1.pp.243–53,2010.
[3] Alsac, O., Stott, B., “Optimal load flow with steady state security”, IEEE Transactions on Power Apparatus System, Vol.93, No.3, pp.745–51, 1974.
[4] Shoults, R., Sun, D., “Optimal power flow based on P–Q decomposition”, IEEE Transactions on Power Apparatus System, Vol.101, No.2, pp.397–405, 1982.
[5] Mota-Palomino, R., Quintana, VH., “Sparse reactive power rescheduling by a penalty-function linear programming technique”, IEEE Transactions on Power System, Vol.1, No.3, pp.31–9, 1983.
[6] Burchett, RC., Happ, HH., Vierath, DR., “Quadratically convergent optimal power flow”, IEEE Transactions on Power Apparatus System, Vol.103, pp.3267–76, 1984.
[7] Ambriz-Perez, H., Acha, E., Fuerte-Esquivel, CR., “Advanced SVC models for Newton-Raphson load flow and newton optimal power flow studies”, IEEE Transactions on Power Systems, Vol.15, No.1, pp.129-36, 2000.
[8] Wei, H., Sasaki, H., Kubokawa, J., Yokoyama, R.. “An interior point nonlinear programming for optimal power flow problems whit a novel structure data”, IEEE Transactions on Power System, Vol.13, pp.870–7, 1998.
[9] Yan, X., Quantana, VH., “Improving an interior point based OPF by dynamic adjustments of step sizes and tolerances”, IEEE Transactions on Power System, Vol.14, No.2, pp.709–17, 1999.
[10] Momoh, JA., Zhu, JZ., “Improved interior point method for OPF problems”, IEEE Transactions on Power System, Vol.14, No.3, pp.1114–20, 1999.
[11] Lai, LL., Ma,JT., “Improved genetic algorithms for optimal power flow under both normal and contingent operation states”, International Journal of Electrical Power& Energy System, Vol.19,No.5, pp.287–92,1997.
[12] Bakirtzis, AG., Biskas, PN., Zoumas, CE., Petridis, V., “Optimal power flow by enhanced genetic algorithm”, IEEE Transactions on Power System,Vol.17.No.2, pp.229–36,2002.
[13] Roa-Sepulveda, CA., Pavez-lazo, BJ., “A solution to the optimal power flow using simulated annealing”, International Journal of Electrical Power& Energy System, Vol.25, No1, pp.47–57,2003.
[14] Varadarajan, M., Swarup, kS., “Solving multi-objective optimal power flow using differential evolution”, IET Generation Transmission Distribution, Vol.2, No.5, pp.720–30, 2008.

[15] Abou El Ela, AA., Abido, MA., Spea, SR., "optimal power flow using differential evolution algorithm", Electrical Power System Research Vol.80, No.7 , pp.878–85, 2010.
[16] Yuryevich, J., Wong, KP., "Evolutionary based optimal power flow algorithm", IEEE Transactions on Power System, Vol.14, No.4, pp.1245–50, 1999.
[17] Sood, YR., "Evolutionary programming based optimal power flow and its validation for deregulated power system analysis", International Journal of Electrical Power& Energy System, Vol.29, No.1, pp.65–75, 2007.
[18] Abido, MA., "Optimal power flow using particle swarm optimization", International Journal of Electrical Power& Energy System, Vol.24, No.7, pp.563–71, 2002.
[19] Kim, JY., Mun, KJ., Kim, HS., Park, JH., "Optimal power system operation using parallel processing system and PSO algorithm", International Journal of Electrical Power& Energy System, Vol.33, No.8, pp.1457–61, 2011.
[20] Duman, S., Güvenç, U., Sönmez, Y., Yörükeren, N., "Optimal power flow using gravitational search algorithm", Energy Conversion and Management, Vol.59, pp.86–95, 2012.
[21] Warren Liao, T., "Two hybrid differential evolution algorithms for engineering design optimization", Applied Soft Computing, Vol.10, No.4, pp.1188–1199, 2010.
[22] Oysu, C., Bingul, Z., "Application of heuristic and hybrid-GASA algorithms to tool-path optimization problem for minimizing airtime during machining", Engineering Applications of Artificial Intelligence, Vol.22, pp.389–396, 2009.
[23] He, D., Wang, F., Mao, Z., "A hybrid genetic algorithm approach based on differential evolution for economic dispatch with valve-point effect", International Journal of Electrical Power & Energy Systems, Vol.30, No1, pp.31–38, 2008.
[24] Li, C.,Zhou, J., "Parameters identification of hydraulic turbine governing system using improved gravitational search algorithm", Energy Conversion and Management, Vol. 52, pp. 374-381, 2011.
[25] Rezaei Adaryani, M., Karami, A., "Artificial bee colony algorithm for solving multi-objective optimal power flow problem ", Electrical Power& Energy System, Vol.53, pp. 219–230, 2013.
[26] Ghasemi, M., Ghavidel, M., Rahmani Sh., "A novel hybrid algorithm of imperialist competitive algorithm and Teaching learning algorithm for optimal power flow problem with non-Smooth cost functions", Engineering Applications of Artificial Intelligence, Vol.29, pp.54-69, 2014.
[27] Niknam, T., Narimani, MR., Jabbari, M., Malekpour, AR., "A modified shuffle frog leaping algorithm for multi-objective optimal power flow", Energy, Vol.36, pp.6420–32,2011.
[28] Sayah, S., Zehar, Kh., "Modified differential evolution algorithm for optimal power flow with non-smooth cost function", Energy Conversion and Management , Vol.49, pp.3036–42,2008.
[29] Bakirtzis, AG., Biskas, PN., Zoumas, CE., Petridis, V., "Optimal power flow by enhanced genetic algorithm", IEEE Transactions on Power System, Vol17, No.2, pp.229–36, 2002.
[30] Niknam, T., Narimani, M.R., Azizipanah-Abarghooee, R., "A new hybrid algorithm for optimal power flow considering prohibited zones and valve point effect", Energy Conversion and Management, Vol.58, pp.197–206, 2012.
[31] MATPOWER.<http://www.pserc.cornell.edu/matpower>.
[32] Vaisakh, K., Srinivas, L.R., "Evolving ant direction differential evolution for OPF with non-smooth cost functions", Engineering Applications of Artificial Intelligence, Vol.24, pp.426–436, 2011.