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AN IMPROVED PSOGSA ALGORITHM USING CHAOTIC MAPS FOR SOLVING THE COMBINED ECONOMIC AND EMISSION DISPATCH PROBLEM

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Abstract

One of the important problems in the management and exploitation of power systems is the minimization of fuel costs and the emission of toxic gases in thermal power plants by adjusting the output power of each generator. This problem is known as the combined economic emission dispatch (CEED) problem. This paper proposes Chaotic PSOGSA algorithm for solving the CEED problem. This algorithm is an improved variant of the PSOGSA algorithm that uses chaotic maps in the gravitational constant formula. Chaotic PSOGSA has an improved exploration, resulting in better characteristics than PSOGSA. The characteristics of the proposed algorithm were evaluated in the paper on a standard IEEE test system with 30 nodes and six generators. Based on the test results, it was found that Chaotic PSOGSA has better characteristics than the algorithms used in other published works.

Keywords: Combined economic emission dispatch; PSOGSA; chaotic maps

INTRODUCTION

Combined Economic and Emission Dispatch (CEED) is the adjustment of the output power of a certain number of generators in thermal power plants at a given load and at given constraints in the power system, minimizing fuel costs and the emission of toxic gases. The functions that describe the emission of toxic gases and fuel costs are non-linear and non-convex, so the CEED problem in the published literature is solved by metaheuristic optimization algorithms that provide approximate solutions. In published papers, a large number of metaheuristic algorithms were proposed to obtain the most accurate and fastest solution of the CEED problem [1], [2], [3]. The speed and accuracy of these algorithms affect the quality of the software they are incorporated into, which is used to manage gas emissions and fuel costs in the thermal power plant. In this paper, we use a variant of the PSOGSA algorithm improved by Gauss/mouse chaotic map to solve the CEED problem. Previously, it was shown in [4] that the introduction of chaotic maps in the gravitational constant formula of GSA algorithm improves the characteristics of GSA algorithm. It was later shown in [5] that the characteristics of hybrid PSOGSA (consisting of GSA and PSO) also improve when chaotic maps are introduced in the same way. In [5], the concrete problem of optimal power flows in the power system using Chaotic PSOGSA was solved. The aim of this work is to show that Chaotic PSOGSA can be effectively applied to solve the CEED problem with better results compared to other algorithms that have been applied in the published literature to solve the same problem.

CEED MODEL

The generator fuel cost function in a thermal power plant usually has a quadratic form:

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$$F_g\left(P_g\right)=a_g+b_g P_g+c_g P_g^2, g= 1, 2,\ldots,G \quad (1)$$

where F_g (\$/h) is the fuel cost of the g-th generator, P_g (MW) is the output power of the g-th generator, and a_g, b_g, and c_g are coefficients. The function F_g becomes non-convex when taking into account the change in power due to the sequential opening of the valves in a thermal power plant (valve point effect) [6]:

$$\begin{aligned}F_g\left(P_g\right)&=a_g+b_g P_g+c_g P_g^2+\\&+\left|d_g\sin\left(e_g\left(P_g^{\min}-P_g\right)\right)\right|\end{aligned} \quad (2)$$

where d_g and e_g are the coefficients related to the valve point effect and $P_g^{\min}$ is the lower limit power of the g-th generator.

The function that models the emission of gases in the thermal power plant is the sum of the quadratic and exponential functions of the output power of the generator [7], [8]:

$$E_g\left(P_g\right)=\alpha_g+\beta_g P_g+\eta_g P_g^2+\xi_g\exp\left(\lambda_g P_g\right) \quad (3)$$

where E_g (t/h) is the amount of gases emitted during the operation of the g-th generator, P_g (MW) is the output power of the g-th generator, α_g, β_g, η_g, ξ_g and λ_g are emission coefficients.

If (1) and (2) are combined with (3), the following function is obtained [9]:

$$FE=w\sum_{g\in G}F_g\left(P_g\right)+(1-w)\gamma\sum_{g\in G}E_g\left(P_g\right) \quad (4)$$

where γ is the scaling factor, w is the weighting factor whose value is taken in the range $0 < w < 1$, and G is the total number of generators under consideration, connected to the system. The CEED problem is solved by choosing the factor w and then minimizing the function (4). By choosing the upper limit of the weight factor, $w = 1$, the total fuel cost ($\sum_{g\in G}F_g\left(P_g\right)$) is minimized, and by choosing the lower limit of w, $w = 0$, the total emission ($\sum_{g\in G}E_g\left(P_g\right)$) is minimized, while the choice of other values of the weight factor corresponds to the simultaneous minimization of fuel costs and gas emissions. The scaling factor γ is applied to solve function (4) as a single-objective optimization problem instead of a two-objective one.

Minimization is performed for the given power limits of each generator, i.e.,

$$P_g^{\min}\le P_g\le P_g^{\max} \quad (5)$$

where $P_g^{\min}$, $P_g^{\max}$ and P_g are the minimum, maximum and actual power of the g-th generator, and for a given balance between the power produced and the power consumed, i.e.

$$\sum_{g\in G}P_g-P_D-P_{loss}=0, \quad (6)$$

where P_D is the total power of all consumers, and P_{loss} is the power loss in the transmission system.

Power losses in the transmission system, P_{loss}, are expressed as a quadratic function of the current generator power, i.e. from Kron's formula [9], as:

$$P_{loss}=\sum_{g\in G}\sum_{j\in G}P_g B_{gj}P_j+\sum_{g\in G}B_{0g}P_g+B_{00} \quad (7)$$

where B_{gj} i B_{0g} are the coefficients of the *B-loss* matrix and B_{00} is a constant.

To satisfy the constraint (6), during the iterative optimization process, one of the generators (e.g., generator G) is selected as a dependent (slack) generator. For that generator, the output power value, P_G, is calculated in each iteration from the following equation:

$$P_G=P_D+P_{loss}-\sum_{g=1}^{G-1}P_g \quad (8)$$

CHAOTIC PSOGSA

To solve the CEED problem we use the Chaotic PSOGSA by introducing a

Gauss/mouse chaotic map into the gravitational constant of PSOGSA. PSOGSA is a hybrid algorithm [10] consisting of PSO [11] and GSA [12] algorithms. It was previously shown in [4] that by introducing chaotic maps into the gravitational constant of the GSA algorithm, better characteristics of this algorithm are obtained. In this paper, we get better characteristics of Chaotic PSOGSA than PSOGSA. The equations in PSOGSA for updating the current velocity, $\mathbf{v}_i(t)$, and current position (solution candidate), $\mathbf{x}_i(t)$, of search agent i, during the iterative process are as follows:

$$\mathbf{v}_i(t+1) = r_0 \cdot \mathbf{v}_i(t) + C_1 \cdot r_1 \cdot \mathbf{a}_i(t) + \\ + C_2 \cdot r_2 \cdot \left(\mathbf{gbest}(t) - \mathbf{x}_i(t)\right) \quad (9)$$

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t+1) \quad (10)$$

where r_0, r_1 and r_2 are uniformly distributed random numbers in the interval [0,1]; r_0 is the inertia weight that balances global search and local search; C_1 and C_2 are the acceleration coefficients; ***gbest*** (t) is the best position of all search agents so far; $\mathbf{a}_i(t)$ is the acceleration of i-th search agent in current iteration t, which depends on the gravitational constant *G*' [12]; In [12] *G*' defines the intensity of gravitational forces between search agents, and it decreases over time (iterations) to control the accuracy of the search. *G*' is a function of the initial value (G_0) and time. Therefore, *G*' allows agents to have larger steps in the initial iterations and smaller ones in the final iterations. In this way, *G'* balances exploration and exploitation.

In this paper, we embed a Gauss/mouse chaotic map in the formula for *G*', which changes *G*' chaotically during each iteration and thus improves the exploration and convergence rate. We express the gravitational constant as follows:

$$G^{'}(t) = C_{g/m}^{norm}(t) + G_0 \cdot \exp(-\alpha \cdot t / t_{\max}) \quad (11)$$

where $C_{g/m}^{norm}(t)$ is the normalized Gauss/mouse chaotic map in iteration t, G_0 is the initial gravitational constant, α is the descending coefficient, and t_{max} is the maximum number of iterations.

The procedure for solving the CEED problem using Chaotic PSOGSA is as follows: First, N randomly selected search agents are generated and represented by the vector of their position $\mathbf{x}_i$ in the search space. The elements of this vector are the output powers, P_i^k, of generators, excluding the power of the slack generator G. The position of i-th search agent is defined as follows:

$$\mathbf{x}_i = \left[P_i^1, ..., P_i^k, ..., P_i^{G-1}\right], \quad i = 1, 2, ...N$$

The power P_G of the slack generator is calculated in each iteration using the equation (8). In the iterative procedure, the fitness of each search agent is computed using the objective function (4). In each iteration, **gbest** (t), $\mathbf{a}_i(t)$, $G^{'}(t)$, $\mathbf{x}_i(t)$ and $\mathbf{v}_i(t)$ are updated. This procedure is repeated until the end criterion is met. The flowchart for solving the CEED problem using Chaotic PSOGSA is given in Figure 1.

SIMULATION RESULTS

Testing of the Chaotic PSOGSA algorithm in this paper is performed on a standard IEEE test system with 30 nodes, 6 generators and a total consumption of 283.4 MW. The effect of valve point effect in thermal power plants and power losses in the system are taken into account. The *B-loss* matrix, cost and emission coefficients for the calculation of losses in the system are taken from [9]. The Chaotic PSOGSA implementation is carried out on a 1.3 GHz platform with 8 GB RAM using MATLAB R2017a. The best values obtained after 30 runs of the algorithm are taken as results. The error tolerance value when calculating

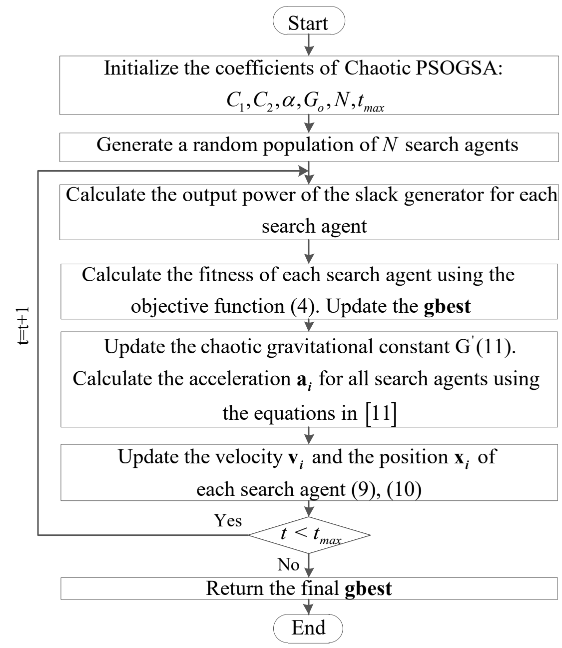

***Fig. 1**. Flowchart of the Chaotic PSOGSA algorithm for solving the CEED problem.*

the losses and power of the slack generator is $\delta = 10^{-6}$ MW, while the scaling factor γ_{NOx} is 1,000 (\$/t). Minimization is performed using the objective function (4) with three values of the weighting factor: $w = 1$ (minimization of fuel costs), $w = 0$ (minimization of NO_x emissions) and $w = 0.5$ (simultaneous minimization of fuel costs and NO_x emissions). The results obtained using Chaotic PSOGSA are compared with the results obtained using the two following algorithms proposed in published papers for solving the CEED problem: PSOGSA [13] and MSA [14]. The coefficients of the tested algorithms applied in the simulation are given in Table 1.

***Table 1**. Coefficients of the algorithms.*

PSOGSA and Chaotic PSOGSA						MSA		
N	T	G_0	α	C_1	C_2	N	t_{max}	T_c
50	300	1	20	0.5	1.5	50	500	6

Table 2 shows the minimum and mean values of the results, standard deviations (SD) and computation times for the applied algorithms.

***Table 2**. Best, mean, SD values and computation time were obtained using Chaotic PSOGSA, PSOGSA, and MSA.*

Algoritam	Values	Chaotic PSOGSA	PSOGSA	MSA
Minimization of fuel cost ($w = 1$)	Best	**635.82043473**	635.83940325	635.82880914
	Mean	**636.49895796**	656.9557	639.62799639
	SD	**2.81447639**	15.0957	6.62733667
	Time (s)	**1.4251**	3.3054	4.9703
Minimization of NO_x emission ($w = 0$)	Best	**0.19417851**	**0.19417851**	**0.19417851**
	Mean	**0.19417851**	0.20430530	**0.19417851**
	SD	**2.60589e-11**	7.090474e-03	2.117882e-09
	Time (s)	3.6597	**1.6088**	4.74917774
Minimization of fuel costs and emission simultaneously ($w = 0.5$)	Best	**430.85141375**	430.85252874	430.85498752
	Mean	432.29140727	445.891749958	**431.28383714**
	SD	11.00106305	24.02610905	**0.68471876**
	Time (s)	1.9816	**1.6975**	2.8692

It follows from Table 2 that the minimum value of fuel cost, obtained using Chaotic PSOGSA, is the smallest compared to_the minimum values obtained using the other two tested algorithms. The minimum emission values of NO_x gases are the same in cases of application of Chaotic PSOGSA, PSOGSA and MSA. The SDs of the results obtained by Chaotic PSOGSA are smaller than the SDs of the results obtained by PSOGSA and higher than the SDs of MSA.

Table 3 shows the best values of generators' output powers, fuel costs and gas emissions, obtained by applying Chaotic PSOGSA for $w = 1$, $w = 0$ and $w = 0.5$. Figure 2 shows the Chaotic PSOGSA, PSOGSA and MSA convergence curves in

***Table 3**. The best values of output power, fuel costs, and gas emissions, were obtained using Chaotic PSOGSA.*

	$w = 1$	$w = 0$	$w = 0.5$
P_1 (MW)	4.99963	41.09248	4.99999
P_2 (MW)	12.39288	46.36680	18.65873
P_3 (MW)	83.53982	54.44145	79.92917
P_4 (MW)	74.81549	39.03722	74.81325
P_5 (MW)	79.80016	54.44575	78.08865
P_6 (MW)	29.73322	51.54931	28.86638
P_{loss} (MW)	1.88119	3.53302	1.95617
Fuel cost ($/h)	**635.82043**	-	638.90730
NO_x (ton/h)	-	**0.194178**	0.222796

the case of minimization of fuel costs (w = 1). From Figure 2, it can be seen that Chaotic PSOGSA converges to the minimum value for a smaller number of iterations compared to PSOGSA and MSA. Figure 2 shows that the initial convergence rates are high for all three algorithms.

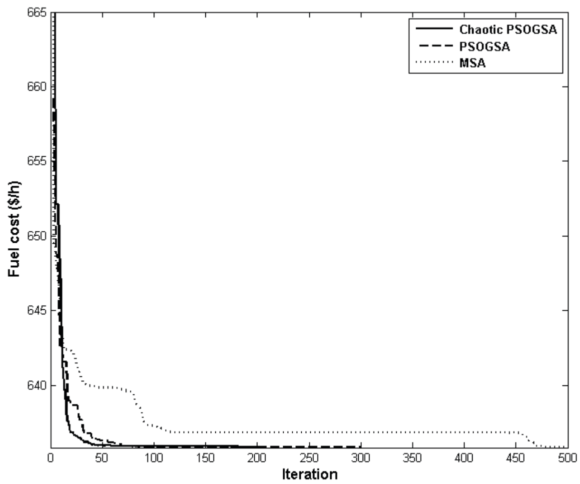

***Fig. 2**. Convergence curves of Chaotic PSOGSA, PSOGSA and MSA in the case of minimization of fuel costs*

CONCLUSION

In this paper, the Chaotic PSOGSA algorithm is proposed for solving the CEED problem. The performance of this algorithm in solving the CEED problem was evaluated on a standard IEEE test system with 30 nodes and 6 generators. When testing the algorithm, the valve point effect in thermal power plants and power losses in the power system were taken into account. The results of testing the Chaotic PSOGSA are compared with the results of the PSOGSA and MSA algorithms proposed in the published literature for solving the CEED problem. By comparing the tested algorithms, we found that Chaotic PSOGSA gives (i) the best values of minimum fuel costs, (ii) the same minimum emission values of NO_x gases as PSOGSA and MSA, (iii) the best convergence, (iv) the best SD in the case of minimization of fuel cost and emission, and comparable values of SD to those obtained using PSOGSA and MSA in the case of simultaneous minimization, (v) the shortest or comparable computation time to those obtained using PSOGSA and MSA.

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