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Combined Economic Emission Dispatch Problem of Thermal Generating Units Using Grey Wolf Optimization

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Abstract
In this paper, a new meta-heuristic algorithm, called grey wolf optimization (GWO) is presented to solve combined economic and emission dispatch (CEED) problem considering transmission losses. GWO is inspired by grey wolves, to mimic the hierarchy of leadership and hunting mechanism of grey wolves in nature. The effectiveness of the proposed algorithm has been tested on the standard IEEE 30-bus test system and the results were compared with other methods reported in recent literature. The simulation results show that the proposed algorithm outperforms previous optimization methods.
Keywords: *Economic dispatch, emission dispatch, combined economic emission dispatch, grey wolf optimization.*

1. Introduction

Optimization of the modern power system plays a major role in thermal power plants energy production. The challenges of the engineers are to optimize the real power of the generating units and to minimize the fuel cost of the power plant. Economic dispatch (ED) is one of the most fundamental issues in operation and control of power systems to allocate generations among the committed units. The main goal of the ED problem is to determine the amount of real power contributed by online thermal generators satisfying load demand at any time subject to unit and system constraints so as the total generation cost is minimized. Therefore, it is very important to solve the problem as quickly and precisely as possible [1, 2]. Therefore, recently most of the researchers made studies for finding the most suitable power values produced by the generators depending on fuel costs. In these studies, they produced successful results by using various optimization algorithms [3-5]. Despite the fact that the traditional ED can optimize generator fuel costs, it still can not produce a solution for environmental pollution due to the excessive emission of fossil fuels.

Currently, a large part of energy production is done with thermal sources. Thermal power plant is one of the most important sources of carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) which create atmospheric pollution [6]. Emission control has received increasing attention owing to increased concern over environmental pollution caused by fossil based generating units and the enforcement of environmental regulations in recent years [7]. Numerous studies have emphasized the importance of controlling pollution in electrical power systems [8].

Combined economic and emission dispatch (CEED) has been proposed in the field of power generation dispatch, which simultaneously minimizes both fuel cost and pollutant emissions. When the emission is minimized the fuel cost may be unacceptably high or when the fuel cost is minimized the emission may be high. A number of methods have been presented to solve CEED problems such as multi-objective differential evolution algorithm [9], genetic algorithm [10-12], simulated annealing [13], biogeography-based optimization [14], modified bacterial foraging algorithm [15], particle swarm optimization [16-18], artificial bee colony algorithm [19-21], gravitational search algorithm [22], moth swarm algorithm [23], and adaptive wind driven optimization [24].

In this paper, GWO algorithm has been used to solve the CEED problem considering transmission loss. Combined economic emission dispatch (CEED) solution which was performed using GWO algorithm was tested on the standard IEEE 30-bus 6-generator test system. The results were compared to those reported in the literature.

2. Problem Formulation

The CEED problem targets to find the optimal combination of load dispatch of generating units and minimizes both fuel cost and emission while satisfying the total power demand. Therefore, CEED consists of two objective functions, which are economic and emission dispatches. Then these two functions are combined to solve the problem. The CEED problem can be formulated as follows [11]:

$$F_T = Min\ f\left(FC, EC\right) \quad (1)$$

where F_T is the total generation cost of the system, FC is the total fuel cost of generators and EC is the total emission of generators.

2.1 Minimization of Fuel Cost

The ED problem can be formulated in a quadratic form as follows [11]:

$$FC = \sum_{i=1}^{N}\left(a_i P_i^2 + b_i P_i + c_i\right) \quad (2)$$

where P_i is the power generation of the ith unit; a_i, b_i, and c_i are fuel cost coefficients of the i th generating unit and N is the number of generating units.

2.2 Minimization of Emission

The classical ED problem can be obtained by the amount of active power to be generated by the generating units at minimum fuel cost, but it is not considered as the amount of emissions released from the burning of fossil fuels. Total amount of emissions such as SO_2 or NO_X depends on the amount of power generated by until and it can be defined as the sum of quadratic and exponential functions and can be stated as [11]:

$$EC = \sum_{i=1}^{N}\left(\alpha_i P_i^2 + \beta_i P_i + \gamma_i + \eta_i \exp(\delta_i P_i)\right) \quad (3)$$

where α_i, β_i, γ_i, η_i and δ_i are emission coefficients of the ith generating unit.

2.3 Combined Environmental Economic Dispatch

CEED is a multi-objective problem, which is a combination of both economic and environmental dispatches that individually make up different single problems. At this point, this multi-objective problem needs to be converted into single-objective form in order to fulfill optimization. The conversion process can be done by using the price penalty factor [11]. However, the single-objective CEED can be formulated as shown in equation (4):

$$F_T = (w * FC + (1-w) * h * EC) \quad (4)$$

under the following condition,

$$0 \le w \le 1 \quad (5)$$

where w is weighting factor: w=1 (fuel cost minimization), w=0 (NOx emission minimization), and w=0.5 (CEED minimization) and h is the price penalty factor.

2.4 Problem Constraints

There are two constraints in the EED problem which are power balance constraint and maximum and minimum limits of power generation output constraint.

2.4.1 Active Power Balance Equation

For power balance, an equality constraint should be satisfied. The total generated power should be the same as total load demand plus the total line loss.

$$P_D = \sum_{i=1}^{N} P_i - P_{Loss} \quad (6)$$

where P_D is the total load demand and P_{Loss} is total transmission losses. The transmission losses P_{Loss} can be calculated by using B matrix technique and is defined by (7) as,

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \quad (7)$$

where B_{ij} is coefficient of transmission losses and the B_{0i} and B_{00} is matrix for loss in transmission which are constant under certain assumed conditions.

2.4.2 Minimum and Maximum Power Limits

Generation output of each generator should lie between minimum and maximum limits. The corresponding inequality constraint for each generator is

$$P_i^{\min} \le P_i \le P_i^{\max} \ \text{ for } \ i = 1,2,\cdots,N \quad (8)$$

where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum outputs of the ith generator, respectively.

3. Grey Wolf Optimization

Grey Wolf Optimizer (GWO) is a new population based meta-heuristic algorithm proposed by Mirjalili et al. in 2014 [25]. The grey wolves mostly like to live in a pack and one of the most important features is their very strict social hierarchy. The main leader of the pack is called alpha. The alpha wolf is the most predominant wolf in the pack as his/her orders were followed by rest of the pack. The alpha wolf is one of the most important members in terms of managing the pack.

The second important one is called beta. They are also known as sub-ordinate wolves as they help alpha in their respective work. They act as advisor to alpha and commander to the rest of the wolves in the pack. The third one is called Delta. They submitted themselves to the alphas and betas but dominate the omegas. The fourth one which are lower ranking wolves are called omega. They have to submit themselves to all other members in the pack.

In another important thing among the grey wolves is their hunting mechanism which includes tracking, chasing, encircling and harassing the prey until they stop moving. Then they attack the prey. The mathematical model of this model is discussed as following.

3.1. Social Hierarchy

When mathematical model of GWO is designed we will consider the first fitness solution as alpha (α), second best solution as beta (β), and the third best solution as delta (δ). The rest of the solutions are assumed as omega (ω). The hunting mechanism is decided by α, β, and δ, and the ω wolves have to follow them.

3.2. Encircling Prey

As the grey wolves encircle prey during the hunt, so their mathematical model which represents their encircling behavior are discussed as below:

$$D = (C.X_p(t)-X_w(t)) \quad (9)$$

$$X_w(t+1) = X_p(t)-A.D \quad (10)$$

where ‘t’ indicates the current iteration, A and C are coefficient vectors, X_p is the position of prey and X_w is the position of grey wolf.
The vector A and C are given as:

$$A = 2a.r_1-a \quad (11)$$

$$C = 2.r_2 \quad (12)$$

Here r_1, r_2 are random vector between 0 to 1, and value of ‘a’ is linearly decreased from 2 to 0.

The grey wolf can update their position according to equation (9) and (10).

3.3. Hunting

As we know that the grey wolf firstly recognizes the prey and then encircles them to hunt. The hunt is usually decided by alpha and beta, delta also participate in hunting occasion. So mathematically in the hunting procedure we take alpha, beta and delta as the best candidate solution and omega have to update its position according to the best search agent. The mathematical model for hunting is shown below:

$$D_\alpha = (C_1.X_\alpha(t)-X(t)) \quad (13)$$

$$D_\beta = (C_2.X_\beta(t)-X(t)) \quad (14)$$

$$D_\delta = (C_3.X_\delta(t)-X(t)) \quad (15)$$

$$X_1 = X_\alpha - A_1.D_\alpha \quad (16)$$

$$X_2 = X_\beta - A_2.D_\beta \quad (17)$$

$$X_3 = X_\delta - A_3.D_\delta \quad (18)$$

$$X(t+1) = (X_1+X_2+X_3)/3 \quad (19)$$

3.4. Search for Prey

As we know that the grey wolves finish their hunt by attacking the prey. In mathematical model we have ‘A’ a random variable having values in the range [-2a, 2a] where ‘a’ is decreased from 2 to 0. When the value of ‘A’ lies within [-1, 1] then the next position of search agent is between its current position and position of prey.

The pseudo code of the GWO algorithm is presented in Table 1.

Table 1 Pseudo code of GWO [25]

```
Grey Wolf Optimizer
Initialize the grey wolf population Xi (i=1, 2, ..., n)
Initialize a, A, and C
Calculate the fitness of each search agent
Xα = the best search agent
Xβ = the second best search agent
Xδ = the third best search agent
while (t < Max number of iterations)
    for each search agent
        Update the position of the current search agent by (19)
    end for
    Update a, A, and C
    Calculate the fitness of all search agents
    Update Xα, Xβ, and Xδ
    t=t+1
end while
Return Xα
```

4. Simulation Results

The proposed GWO algorithm is tested on the standard IEEE 30-bus power system with six-generating units in order to investigate its effectiveness. The single-line diagram of the IEEE 30-bus test system is shown in Figure 1 and the detailed data are given in [21, 22]. The parameters of all thermal units (generation limits, fuel cost and NO_x emission coefficients) are presented in Table 2, followed by *B*-loss coefficients are presented in Table 3. The load demand of the system is 283.4 MW. The values of GWO algorithm for solving CEED problem in this paper are designated as follow: the number of population size, NP = 30; and the number of iterations, maxIter = 200.

The best solutions for power outputs, fuel cost and NO_x emission obtained by using GWO for *w*=1, *w*=0, and *w*=0.5 are given in Table 4. The results obtained by GWO for the test system along with corresponding data from the literature are summarized in Table 5. As can be seen in Table 5, the GWO provided better values for the minimum fuel cost and NO_x emission in regard to the values obtained by the algorithms proposed in [9, 14, 16, 22, 23, 24].

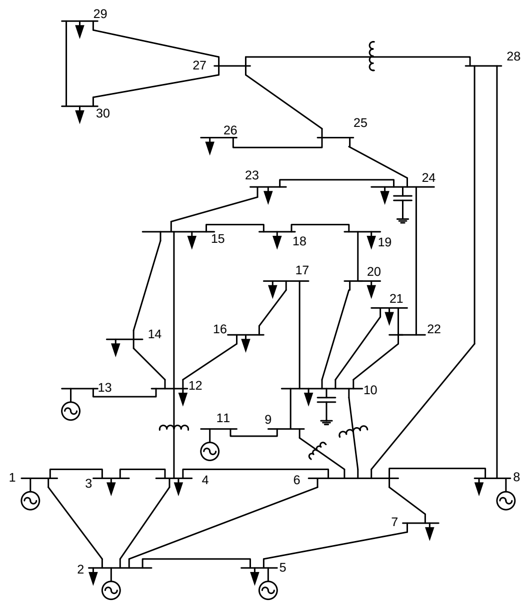

Figure 1   Single-line diagram of IEEE 30-bus test system [20]

Table 2   Generation limits, fuel cost and NO_x emission coefficients for IEEE 30-bus test system [21]

Unit	P_i^{min}	P_i^{max}	a_i	b_i	c_i	α_i	β_i	γ_i	η_i	δ_i
1	5	150	10	200	100	4.091e-2	-5.554e-2	6.940e-2	2.0e-4	2.857
2	5	150	10	150	120	2.543e-2	-6.047e-2	5.638e-2	5.0e-4	3.333
3	5	150	20	180	40	4.258e-2	-5.094e-2	4.586e-2	1.0e-6	8.0
4	5	150	10	100	60	5.326e-2	-3.550e-2	3.380e-2	2.0e-3	2.0
5	5	150	20	180	40	4.258e-2	-5.094e-2	4.586e-2	1.0e-6	8.0
6	5	150	10	150	100	6.131e-2	-5.555e-2	5.151e-2	1.0e-5	6.667

Table 3 Transmission loss coefficients [21]

$$B_{ij} = \begin{bmatrix} 0.1382 & -0.0299 & 0.0044 & -0.0022 & -0.0010 & -0.0008 \\ -0.0299 & 0.0487 & -0.0025 & 0.0004 & 0.0016 & 0.0041 \\ 0.0044 & -0.0025 & 0.0182 & -0.0070 & -0.0066 & -0.0066 \\ -0.0022 & 0.0004 & -0.0070 & 0.0137 & 0.0050 & 0.0033 \\ -0.0010 & 0.0016 & -0.0066 & 0.0050 & 0.0109 & 0.0005 \\ -0.0008 & 0.0041 & -0.0066 & 0.0033 & 0.0005 & 0.0244 \end{bmatrix}$$

$$B_{0i} = \begin{bmatrix} -0.0107 & 0.0060 & -0.0017 & 0.0009 & 0.0002 & 0.0030 \end{bmatrix}$$

$$B_{00} = 0.00098573$$

Table 4. The best solutions obtained by using GWO

w	Generation (MW)						Fuel Cost ($/h)	NO_x Emission (ton/h)	P_{Loss} (MW)
	P_1	P_2	P_3	P_4	P_5	P_6			
1	12.9741	29.3484	55.8379	103.2595	47.0851	37.3191	605.7313	0.2050	2.4240
0	38.3291	46.2245	51.7516	53.2664	41.6969	55.6465	636.9267	0.1874	3.5150
0.5	19.7310	36.8678	62.0442	74.3450	57.3938	35.4003	611.6703	0.1942	2.3820

Table 5. Comparison of best solution

Methods	Fuel cost minimization (w=1)		NO_x emission minimization (w=0)		CEED minimization (w=0.5)	
	Fuel cost ($/h)	NO_x emission (ton/h)	Fuel cost ($/h)	NO_x emission (ton/h)	Fuel cost ($/h)	NO_x emission (ton/h)
MODE [9]	606.41060	0.2221	643.5190	0.1942	614.1700	0.2043
MBFA [14]	607.6700	0.2198	644.4300	0.1942	616.4960	0.2002
MOPSO [16]	607.7900	0.2193	644.7400	0.1942	615.0000	0.2021
GSA [22]	605.9984	0.2207	646.2070	0.1942	612.2530	0.2036
MSA [23]	605.9984	0.2207	646.2049	0.1942	612.2519	0.2038
AWDO [24]	605.9984	0.2207	646.2070	0.1942	612.2528	0.2036
GWO	**605.7313**	**0.2050**	**636.9267**	**0.1874**	**611.6703**	**0.1942**

5. Conclusions

In this paper, a new approach based on grey wolf optimization (GWO) algorithm has been presented and successfully applied to solve the combined economic emission dispatch problem considering transmission losses. The problem has been formulated as multiobjective optimization problem with competing fuel cost and environmental impact objectives. The effectiveness of proposed algorithm is demonstrated on the standard IEEE 30-bus test system with six generating units. The comparison of the results obtained with other methods reported in the literature shows the superiority of the proposed algorithm and its potential for solving the combined economic emission dispatch problems in large-scale power systems. The results obtained from the test systems have indicated that the proposed technique has better performance in terms of minimum fuel costs and NO_x emissions than other optimization methods reported in the literature.

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