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Thermal Unit Commitment with Environmental Considerations using Modified Water Evaporation Optimization Algorithm

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ABSTRACT: The thermal unit commitment problem involves determining the start-up and shut-down schedules for generating units to meet the forecasted demand at the minimum cost. The commitment schedule must satisfy the other constraints such as the generating limits, spinning reserve, minimum up and down time, ramp level and individual units. In this paper thermal unit commitment problem with emission minimization is solved by modified water evaporation optimization algorithms. The priority list method has been used for to obtain the unit commitment schedule and MWEO algorithm uses to obtain the economic schedule among the committed units for each interval.

KEYWORDS: Thermal unit commitment, Emission, Generation scheduling, Modified water evaporation optimization.

I. INTRODUCTION

Unit commitment which is considered as a large scale, nonlinear, mixed-integer optimization problem plays a very important role in optimal operation of power systems. Solving the UC problem is a complex decision-making process since multiple constraints must be satisfied and a good UC solution method can substantially contribute to annual savings of production cost. The objective of the UC problem is to minimize the total cost of thermal generating units while maintaining sufficient spinning reserve and satisfying the operational constraints of generating units over a given schedule time horizon. Due to the increasing environmental protection the emission is also added to UC problems [1].

An optimal solution to the UC problem in power system operation can be obtained by a complete enumeration. However, the requirement of the excessive computational resource is impossible to be implemented in practice. Therefore, many research efforts have been focused on efficient UC algorithms for lower total production cost and computational time [1].

Over the years, extensive research has been conducted on developing efficient UC algorithm that can be mainly grouped as numerical based techniques and Heuristic search based techniques [2-27] has been proposed. In this paper, the thermal unit commitment problem with emission has been proposed using modified Water Evaporation Optimization (WEO) [26] are implemented to handling ramp rates with the aims of achieving the desired solution accuracy and to reduce the cost and computational effort in 24 hr time horizon.

II. PROBLEM FORMUATION

The main goal of UC is to minimize overall system generation cost over the scheduled time horizon subject to system and operational constraints.

Objective Function

The objective function of the UC problem comprises of the fuel costs of generating units, the start-up costs of the committed units and shut-down costs of the decommitted units. This constrained optimization problem in common is defined as,

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$$Min\,CF = \sum_{t=1}^{T}\sum_{i=1}^{N}\left\{FC_i\left(P_i^t\right)U_i^t + SC_i^t\left(1-U_i^{t-1}\right)U_i^t\right\} \tag{2.1}$$

Where, $FC_i\left(P_i^t\right)$ is the cost function of the i_{th} unit is given by

$$FC_i\left(P_i^t\right) = \sum_{i=1}^{N} a_i\left(P_i^t\right)^2 + b_i P_i^t + c_i \tag{2.2}$$

$$SC_i = \begin{matrix} h\cos t_i\,; & T_i^{down} \le T_i^{off} \le T_i^{down} + cshour_i \\ c\cos t_i\,; & T_i^{off} \ge T_i^{down} + cshour_i \end{matrix} \tag{2.3}$$

FC_i is the fuel cost of i_{th} unit (\$), SC_i^t is the startup cost of i_{th} generating unit (\$). The a_i, b_i, c_i are fuel cost coefficient for i_{th} generating unit and CF is the cost function of on line generating units during time interval of t hours. U_i^t is on/off status of i_{th} generating unit during hour t, P_i^t power output of the i_{th} generating unit during hour t. N is the number of thermal generating units. T is the number of schedule times in hours.

THERMAL UNIT COMMITMENT WITH EMISSION

For many years the environmental impacts were ignored in solving the conventional UC problem. However, the current standards for smart and green electrical grids require the reduction of harmful emissions such as nitrogen oxides (NOx), sulphur dioxide (SO2), and carbon dioxide (CO2). Thus, another objective, emission is included in the UC problem formulation and the release of pollutant from thermal plants into the atmosphere is expressed as,

$$F_{Emission} = \sum_{t=1}^{T}\sum_{i=1}^{N}\left[E_i\left(P_i^t\right)\right] \tag{2.4}$$

$$E_i\left(P_i^t\right) = d_i\left(P_i^2\right) + e_i P_i + f_i \tag{2.5}$$

Where d_i, e_i, f_i are Emission coefficient for i_{th} generating unit and E_i is the emission of unit i in lb.

Constraints

Power balance constraint

Power balance constraint states that, the generated power should be sufficient enough to meet the power demand and is given by,

$$\sum_{i=1}^{N} U_i^t P_i^t \qquad t = 1,2,.....,T \tag{2.6}$$

Generated power limits

The generated power of online generating units should lie between its upper and lower limits as given by,

$$P_{i,\min} U_i^t \le P_i^t \le P_{i,\max} U_i^t \tag{2.7}$$

$P_{i,min}$ and $P_{i,max}$ are the minimum and maximum thermal output power at i_{th} unit.

Spinning reserve requirement

Spinning reserve is essential to maintain system reliability; sufficient spinning reserve must be available at every time period. Usually, the spinning reserve is given as some percentage of the total power demand.

$$\sum_{i=1}^{N} U_i^t P_{i,\max} \ge LD_t + SR_t \tag{2.8}$$

SR_t spinning reserve at hour t, LD_t load demand during hour t.

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Minimum up and down time

This constraint helps to determine shortest time periods during which a unit must be on or down.

$$HR_i^{t,on} \geq MU_i$$
$$HR_i^{t,off} \geq MD_i \quad (2.9)$$

$HR_i^{t,on}$ and $HR_i^{t,off}$ are number of hours at unit i is continuously online and offline unit until t_{th} hour. MU_i is the minimum up time hours and MD_i is the minimum down time hours.

Ramp rate

Because of the physical restrictions on thermal generating units, the rate of generation changes must be limited within certain ranges. The ramp rate limits confine the output movement of a generating unit between adjacent hours.

$$P_i^t - P_i^{t-1} \leq RU_i$$
$$P_i^{t-1} - P_i^t \leq RD_i \quad (2.10)$$

III. WATER EVAPORATION OPTIMIZATION ALGORITHM

The evaporation of water is very important in biological and environmental science. The water evaporation from bulk surface such as a lake or a river is different from evaporation of water restricted on the surface of solid materials. In this WEO algorithm water molecules are considered as algorithm individuals. Solid surface or substrate with variable wettability is reflected as the search space. Decreasing the surface wettability (substrate changed from hydrophility to hydrophobicity) reforms the water aggregation from a monolayer to a sessile droplet.

Such a behavior is consistent with how the layout of individuals changes to each other as the algorithm progresses. And the decreasing wettability of surface can represent the decrease of objective function for a minimizing optimization problem. Evaporation flux rate of the water molecules is considered as the most appropriate measure for updating individuals which its pattern of change is in good agreement with the local and global search ability of the algorithm and make this algorithm have well converged behavior and simple algorithmic structure. The details of the water evaporation optimization algorithm are well presented in **(Kaveh and Bakhshpoori, 2016)**.

In the WEO algorithm, each cycle of the search consists of following three steps (i) Monolayer Evaporation Phase, this phase is considered as the global search ability of the algorithm (ii) Droplet Evaporation Phase, this phase can be considered as the local search ability of the algorithm and (iii) Updating Water Molecules, the updating mechanism of individuals.

(i) Monolayer Evaporation Phase

In the monolayer evaporation phase the objective function of the each individuals Fit_i^t is scaled to the interval [-3.5, -0.5] and represented by the corresponding $E_{sub}(i)^t$ inserted to each individual (substrate energy vector), via the following scaling function.

$$E_{sub}(i)^t = \frac{(E_{\max} - E_{\min}) \times (Fit_i^t - Min(Fit))}{(MaX(Fit) - Min(Fit))} + E_{\min} \quad (3.1)$$

Where E_{max} and E_{min} are the maximum and minimum values of E_{sub} respectively. After generating the substrate energy vector, the Monolayer Evaporation Matrix (MEP) is constructed by the following equation.

$$MEP_{ij}^t = \begin{cases} 1 if\ rand_{ij} \leq \exp(E_{sub}(i)^t) \\ 0 if\ rand_{ij} \geq \exp(E_{sub}(i)^t) \end{cases} \quad (3.2)$$

where MEP_t^{ij} isthe updating probability for the j^{th} variable of the i^{th} individual or water molecule in the t^{th} iteration of the algorithm. In this way an individual with better objective function is more likely to remain unchanged in the search space.

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(ii) Droplet Evaporation Phase

In the droplet evaporation phase, the evaporation flux is calculated by the following equation.

$$J(\theta) = J_o P_o \left(\frac{2}{3} + \frac{\cos^3\theta}{3} - \cos\theta \right)(1 - \cos\theta) \tag{3.3}$$

where J_o and P_o are constant values. The evaporation flux value is depends upon the contact angle Θ, whenever this angle is greater and as a result will have less evaporation. The contact angle vector is represented the following scaling function.

$$\theta(i)^t = \frac{(\theta_{\max} - \theta_{\min}) \times (Fit_i^t - Min(Fit))}{(Max(Fit) - Min(Fit))} + \theta_{\min} \tag{3.4}$$

Where the min and max are the minimum and maximum functions. The Θ_{min} & Θ_{max} values are chosen between $-50^o < \Theta < -20^o$ is quite suitable for WEO. After generating contact angle vector $\Theta(i)^t$ the Droplet Probability Matrix (DEP) is constructed by the following equation.

$$DEP_{ij}^t = \begin{cases} 1 if\ rand_{ij} < J\left(\theta_i^{(t)}\right) \\ 0 if\ rand_{ij} \geq J\left(\theta_i^{(t)}\right) \end{cases} \tag{3.5}$$

where DEP^t_{ij} is the updating probability for the j^{th} variable of the i^{th} individual or water molecule in the t^{th} iteration of the algorithm.

(iii) Updating Water Molecules

In the WEO algorithm the number of algorithm individuals or number of water molecules (nWM) is considered constant in all t^{th} iterations, where t is the number of current iterations. Considering a maximum value for algorithm iterations (t_{max}) is essential for this algorithm to determine the evaporation phase and for stopping criterion. When a water molecule is evaporated it should be renewed. Updating or evaporation of the current water molecules is made with the aim of improving objective function. The best strategy for regenerating the evaporated water molecules is using the current set of water molecules ($WM^{(t)}$). In this way a random permutation based step size can be considered for possible modification of individual as:

$$S = rand.\left(WM^{(t)}\left[permute1(i)(j)\right] - WM^{(t)}\left[permute2(i)(j)\right]\right) \tag{3.6}$$

where rand is a random number in [0,1] range, permute1and permute 2 are different rows of permutation functions. i is the number of water molecule, j is the number of dimensions of the problem. The next set of molecules ($WM^{(t+1)}$) is generated by adding this random permutation based step size multiplied by the corresponding updating probability (monolayer evaporation and droplet evaporation probability) and can be stated mathematically as:

$$WM^{(t+1)} = WM^{(t)} + S \times \begin{cases} MEP^{(t)}\ t \leq t_{\max}/2 \\ DEP^{(t)}\ t > t_{\max}/2 \end{cases} \tag{3.7}$$

Each water molecule is compared and replaced by the corresponding renewed molecule based on objective function. It should be noted that random permutation based step size can help in two aspects. In the first phase, water

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molecules are more far from each other than the second phase. In this way the generated permutation based step size will guarantee global and local capability in each phase.

IV. IMPLEMENTATION OF WEO ALGOTIHM TO SOLVE UC PROBLEM

The detailed algorithmic steps for proposed MWEO algorithm to solve an UC problem are presented below.

Step 1: Initialize total no of generating units, generator power limits, ramp rate limits, minimum uptime, minimum downtime, load demand, number of water molecules, maximum number of algorithm iteration (t_{max}), MEP_{min}, MEP_{max}, DEP_{min}, $DEP_{max.}$

Step 2: Randomly initialize all water molecules.

Step 3: Obtain the ON/OFF status of generating units by applying priority list method and compute the objective function given by Eq. (2.1), Eq. (2.4) and Eq. (2.8) for all water molecules.

Step 4: Check whether *t* (current iteration) $\leq t_{max}/2$.

Step 5: If step 4 is satisfied, then, water molecules are globally evaporated based on monolayer evaporation probability MEP using Eq. (3.2).

Step 6: For $t > (1+ t_{max}/2)^2$, Based on DEP (Eq. 3.5), in the modified evaporation occurs.

Step 7: Generate random permutation based step size matrix according to Eq. (3.6).

Step 8: Generate evaporated water molecules by adding the product of step size matrix and evaporation matrix to the current set of molecules $MWM^{(t)}$ by using Eq. (3.7) and update the matrix of water molecules.

Step 9: Compare and update the water molecules.

Step 10: Return the best water molecule (generator outputs corresponding to the minimized value of CF or E).

Step 11: If the number of iteration of the algorithm (t) becomes larger than the maximum number of iterations (t_{max}), the algorithm terminates. Otherwise go to step 3.

V. SIMULATION RESULTS AND DISCUSSION

In order to demonstrate the performance of MWEO algorithm for solving UC problem with the objective of minimization of emission, the standard 10-unit system is considered and the emission data has been adopted from [27]. Like the fuel cost characteristics, the emission

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TABLE 5.2 TEST RESULTS OF 10-UNIT SYSTEM FOR EMISSION MINIMIZATION

Hour	Generation schedule, MW										Fuel cost, $	SC, $	Emission, lb
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}			
1	216.42	216.42	0	130	136.16	0	0	0	0	0	15333.82	0	516.712
2	206.72	206.72	0	130	126.56	80	0	0	0	0	16982.48	170	541.4215
3	216.76	216.76	68.94	130	137.53	80	0	0	0	0	19403.48	550	696.2372
4	244.99	244.99	88.02	130	162	80	0	0	0	0	21191.81	0	856.8553
5	263.66	263.66	100.63	130	162	80	0	0	0	0	22038.77	0	948.3073
6	301.02	301.02	125.93	130	162	80	0	0	0	0	23736.23	0	1156.948
7	323.99	323.99	130	130	162	80	0	0	0	0	24585.39	0	1274.828
8	348.99	348.99	130	130	162	80	0	0	0	0	25434.93	0	1404.057
9	362.82	362.82	130	130	162	80	72.36	0	0	0	28396.36	520	1771.326
10	384.26	384.26	130	130	162	80	74.48	55	0	0	31283.33	60	2159.202
11	381.88	381.88	130	130	162	80	74.24	55	55	0	33367.22	60	2417.433
12	379.49	379.49	130	130	162	80	74.00	55	55	55	35483.22	60	2685.4
13	384.26	384.26	130	130	162	80	74.48	55	0	0	31283.33	0	2159.202
14	362.82	362.82	130	130	162	80	72.36	0	0	0	28396.36	0	1771.326
15	348.99	348.99	130	130	162	80	0	0	0	0	25434.93	0	1404.057
16	282.34	282.34	113.30	130	162	80	0	0	0	0	22886.91	0	1048.331
17	263.66	263.66	100.66	130	162	80	0	0	0	0	22038.77	0	948.3073
18	301.02	301.02	125.93	130	162	80	0	0	0	0	23736.23	0	1156.948
19	348.99	348.99	130	130	162	80	0	0	0	0	25434.93	0	1404.057
20	384.26	384.26	130	130	162	80	74.48	55	0	0	31283.33	320	2159.202
21	362.82	362.82	130	130	162	80	72.36	0	0	0	28396.36	0	1771.326
22	277.16	277.16	109.80	130	162	80	63.88	0	0	0	24906.63	0	1290.087
23	256.19	256.19	95.62	130	162	0	0	0	0	0	19503.49	0	843.7982
24	224.71	224.71	74.34	130	145.24	0	0	0	0	0	17748.28	0	673.8962

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characteristics of generators are expressed as second-order polynomials. The WEO algorithm parameters for all test systems are shown in **Table 5.1**.The MWEO is implemented on the 10-unit system for minimum emission dispatch and the obtained schedule is presented in **Table 5.2**. The MWEO obtains the total fuel cost of $ 600025 and total emission of 33060 lb. The comparison of results presented in **Table 5.3** indicates that the proposed method has obtained minimum value of emission among the RCGWO [27].

TABLE 5.1 PROBLEM PARAMETERS OF WEO & MWEO ALGORITHM

Problem Parameters	WEO	MWEO
Water Molecules (nWM)	10	10
Maximum Number of Algorithm Iteration (t_{max})	100	100
MEP_{min}	0.03	0.03
MEP_{max}	0.6	0.5
DEP_{min}	0.6	0.5
DEP_{max}	1	1

TABLE 5.3 COMPARISON RESULTS OF TEST SYSTEM 15

Method	Emission, lb
RCGWO	33061.80
WEO	**33061.2650**
MWEO	**33060**

VI. CONCLUSION

The effective unit commitment saves fuel costs and is a necessary contribution to the operating on/off plans of the generating units. In this paper, a modified water evaporation optimization based solution algorithm for solving the unit Commitment problem with emission minimization is presented. The proposed algorithm uses global search and local search to select the committed units and give the economic schedule for each specific hour. This new algorithm produces better results than the existing methods in addition to satisfaction of the system constraints. From the results, it is clear that the proposed method provides the quality solution with low cost and has a potential for on-line implementation.

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