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Unit Commitment Problem solution using Water Evaporation Optimization Algorithm

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ABSTRACT: *This paper has proposed water evaporation optimization (WEO) algorithm for solving thermal Unit Commitment problem. The Unit Commitment problem is a mixed integer problem with many equality and inequality constraints like the minimum down and minimum up time, spinning reserve, and ramp rate so need to a complex optimization process. In this paper the constraint handling of the problem is realized without any penalizing of solutions so a wide range of feasible solutions will be available for final optimum response. The WEO s a novel method which has better performance than its original version and more optimized responses and escape for local minimum areas easily.. The main advantages of HGICA are good quality of the solution and high computational speed, which make it a suitable method for solving optimization problems. This method is carried out for different case studies efficiency of it is proved. Also the obtained results are compared to other optimization methods represented in literature for different scenarios.*

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I. INTRODUCTION

The economic performance of thermal power plants is essential due to the scarcity of fuel. Efficient power scheduling is necessary in power system operations in order to achieve economic and reliable energy production and system operations. This cognitive process can be attained by the UC and profuse literature is available in this context. With the advancement of present soft computing techniques, it is necessary to fetch a better schedule of the generating units for sharing the local load among the available generating units in order to obtain a cost-effective solution. The general objective of UC problem is to minimize system total operating cost over the scheduled time horizon while simultaneously providing sufficient spinning reserve capacity to satisfy a given security level. Moreover, pollutant emission can also be included as objective and considering the practical constraints such as ramp rate limits and reliability in the UC problem will be a welcome perspective. To include all these aspects in this work, the UC process can be mathematically modeled as an optimization problem and the real power generations of generating units are optimized subject to various system and operational constraints.

The UC problem is a highly constrained combinatorial optimization problem and the exact solution can be obtained only by complete enumeration, often at the cost of a prohibitively large computational time requirement for practical power systems. Numerous approaches have been applied to the UC solution and can be categorised into mathematical, heuristic and hybrid methods.

The mathematical approaches are Priority List method [1], Mixed Integer Method [2], Enhanced Adaptive Lagrangian Relaxation method [3], Evolutionary Programming [6] has been proposed in which the UC problem is decomposed into three sub-problems which are solved. Most of these methods suffer with the curse of dimensionality and are commonly getting struck at a local optimal solution. This restriction can be revoked by applying the meta-heuristic techniques to UC problems. The Meta Heuristic Techniques are Fuzzy and Simulated Annealing based dynamic programming [4], Enhanced Simulated Annealing algorithm [5], Genetic Algorithm [7, 8], Invasive weed optimization [12], Quantum Inspired Evolutionary Algorithm [13], Semi definite Programming Relaxation [14], Quasi opposition Teaching Learning based optimization [15], Imperialistic Competition algorithm [16] has been reported to the Unit Commitment problem. The Hebraized algorithms are Genetic Algorithm – Differential Evaluation [9], Fuzzy – Particle Swarm Optimization [10], Lagrangian Relaxation – Particle Swarm optimization [11], GHS – JST Evolutionary algorithm [17], Binary / Real coded Artificial Bee Colony [18], POZ constraint using Dynamic Programming method [20], Hybrid Genetic – Imperialistic Competitive algorithm [21] which are usually randomly search approaches have been developed to find more optimum results and get better computational time than previous approaches. The UCP presented here is a kind of generating scheduling of the thermal units implementation that their output power are constant, but the renewable energy resources due to their nature produce alternative electrical power so their scheduling is different.

Recently, motivated by the shallow water theory, researchers have proposed Water Evaporation Optimization (WEO) algorithm for solving global optimization problem [19]. The WEO algorithm is conceptually simple and easy to implement. The WEO algorithmic search consists of both global and local search. This guarantees that the proposed algorithm is competitive with other efficient well-known meta-heuristics. The WEO algorithm is used for selection of all the fuel and committed all the units.

II. PROBLEM FORMULATION

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 1

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,

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

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

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

FC_i is the fuel cost of i_{th} unit ($), SC_i is the startup cost of i_{th} generating unit ($). 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.

Objective Function 2

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,

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

$$E_i\left(P_i^t\right) = d_i\left(P_i^2\right) + e_i P_i + f_i \tag{3}$$

The 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,

$$\sum_{i=1}^{N} U_i^t P_i^t \qquad t = 1,2,\ldots\ldots,T \tag{4}$$

Generated power limits

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

$$P_{i,\min} U_i^t \le P_i^t \le P_{i,\max} U_i^t \tag{5}$$

$P_{i,min}$ 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.

$$\sum_{i=1}^{N} U_i^t P_{i,\max} \ge LD_t + SR_t \tag{6}$$

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

Minimum up and down time

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

$$\begin{aligned} HR_i^{t,on} &\ge MU_i \\ HR_i^{t,off} &\ge MD_i \end{aligned} \tag{7}$$

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

$$\begin{aligned} P_i^t - P_i^{t-1} &\le RU_i \\ P_i^{t-1} - P_i^t &\le RD_i \end{aligned} \tag{8}$$

III. WATER EVAPORATION OPTIMIZATION

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 [19].

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.

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.

$$E_{sub}(i)^t = \frac{(E_{\max} - E_{\min}) \times \left(Fit_i^t - Min(Fit)\right)}{\left(MaX(Fit) - Min(Fit)\right)} + E_{\min} \tag{9}$$

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.

$$MEP_{ij}^t = \begin{cases} 1 \; if \; rand_{ij} \leq \exp\left(E_{sub}(i)^t\right) \\ 0 \; if \; rand_{ij} \geq \exp\left(E_{sub}(i)^t\right) \end{cases} \tag{10}$$

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

Droplet Evaporation Phase

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

$$J(\theta) = J_o P_o \left(\frac{2}{3} + \frac{\cos^3\theta}{3} - \cos\theta \right)(1 - \cos\theta) \tag{11}$$

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.

$$\theta(i)^t = \frac{(\theta_{\max} - \theta_{\min}) \times \left(Fit_i^t - Min(Fit)\right)}{\left(Max(Fit) - Min(Fit)\right)} + \theta_{\min} \tag{12}$$

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.

$$DEP_{ij}^t = \begin{cases} 1 \; if \; rand_{ij} < J\left(\theta_i^{(t)}\right) \\ 0 \; if \; rand_{ij} \geq J\left(\theta_i^{(t)}\right) \end{cases} \tag{13}$$

where DEP^t_{ij} is the updating probability for the jth variable of the ith individual or water molecule in the tth iteration of the algorithm.

Updating Water Molecules

In the WEO algorithm the number of algorithm individuals or number of water molecules (nWM) is considered constant in all tth 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:

$$S = rand.\left(WM^{(t)}\left[permute1(i)(j)\right] - WM^{(t)}\left[permute2(i)(j)\right]\right) \tag{14}$$

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:

$$WM^{(t+1)} = WM^{(t)} + S \times \begin{cases} MEP^{(t)}\, t \le t_{\max} / 2 \\ DEP^{(t)}\, t > t_{\max} / 2 \end{cases} \tag{15}$$

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 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.

The WEO algorithm can be summarized as follows:

step 1: Initialize all the algorithm and problem parameters, randomly initialize all water molecules.

step 2: Generating water evaporation matrix

Every water molecule follow the evaporation probability rules specified for each phase of the algorithm based on the Eqs. (10) and (13). For t ≤ t_{max} /2, water molecules are globally evaporated based on monolayer evaporation probability MEP by using Eq (10). for t > t_{max} /2, evaporation occurs based on the droplet evaporation probability DEP by using Eq (13). It should be noted that for generating monolayer and droplet evaporation probability matrices, it is necessary to generate the correspondent substrate energy vector and contact angle vector by using Eqs (9) and (12) respectively.

step 3: Generating random permutation based step size matrix

A random permutation based step size matrix is generated according to Eq. (14)

step 4: Generating evaporated water molecules and updating the matrix of water mlecules

The evaporated set of water molecules $VM^{(t+1)}$ is generated by adding the product of step size matrix and evaporation matrix to the current set of molecules $VM^{(t)}$ by using Eq. (15). These molecules are evaluated based on the objective function. For the molecule i (i = 1,2, ...nWM) if the newly generated molecule is better than the current one, the latter should be replaced. Return the best water molecule as the output of the algorithm

step 5: Terminating condition check

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 2.

IV. NUMERICAL SIMULATION RESULTS

The proposed methodology has been tested with standard 10-unit test systems with different cases and the proposed algorithm is developed in Matlab environment and is implemented using Intel (R) Core ™ i5-4200U CPU@1.60 GHz processor. The effectiveness of the proposed WEO algorithm for UC problem has been validated by comparing the simulation results obtained from the other methods available in the literature. The WEO algorithm parameters for all the test systems are chosen as: number of water molecules (nWM) = 10, t_{max} = 100, MEP = 0.03, MEP & DEP = 0.6, DEP = 1.

TEST SYSTEM 1: 10 Unit Systems with ramp rate

In this case study, the 10-unit system with 10% spinning reserve is considered. The ramp rate constraints are imposed in the system and its effect in the test system results are analyzed. The simulation is performed for 100 trials and the obtained best generation schedule for 10-unit system considering ramp rate constraint is presented in **Table 1**.

Table 1 Optimal Classical Uc Schedule Using Weo For The Standard 10-Unit System

Hours	1	2	3	4	5	6	7	8	9	10	Run cost	Start up cost
1	455	245	0	0	0	0	0	0	0	0	13,683.1297	0
2	455	295	0	0	0	0	0	0	0	0	14,554.4997	0
3	455	370	0	0	25	0	0	0	0	0	16,809.4485	900
4	455	455	0	0	40	0	0	0	0	0	18,597.6677	0
5	455	390	0	130	25	0	0	0	0	0	20,020.0195	560
6	455	360	130	130	25	0	0	0	0	0	22,387.0445	1100
7	455	410	130	130	25	0	0	0	0	0	23,261.9795	0
8	455	455	130	130	30	0	0	0	0	0	24,149.3685	0
9	455	455	130	130	85	20	0	0	0	0	27,251.0560	860
10	455	455	130	130	162	33	25	10	0	0	30,057.5503	60
11	455	455	130	130	162	73	25	10	10	0	31,916.0611	60
12	455	455	130	130	162	80	25	43	10	10	33,890.1629	60

13	455	455	130	130	162	33	25	10	0	0	30,057.5503	0
14	455	455	130	130	85	20	25	0	0	0	27,251.0560	0
15	455	455	130	130	30	0	0	0	0	0	24,150.3407	0
16	455	310	130	130	25	0	0	0	0	0	21,513.6595	0
17	455	260	130	130	25	0	0	0	0	0	20,641.8245	0
18	455	360	130	130	25	0	0	0	0	0	22,387.0445	0
19	455	455	130	130	30	0	0	0	0	0	24,150.3407	0
20	455	455	130	130	162	33	25	10	0	0	30,057.5503	490
21	455	455	130	130	85	20	25	0	0	0	27,251.0560	0
22	455	455	0	0	145	20	25	0	0	0	22,735.5210	0
23	455	420	0	0	0	20	0	0	0	0	17,645.3637	0
24	455	344	0	0	0	0	0	0	0	0	15,426.0191	0

The objective value versus iterations for the 10-unit system with ramp rate constraints is shown in **Figure 1**. The converged results indicate that the proposed algorithm is highly competitive with recent techniques.

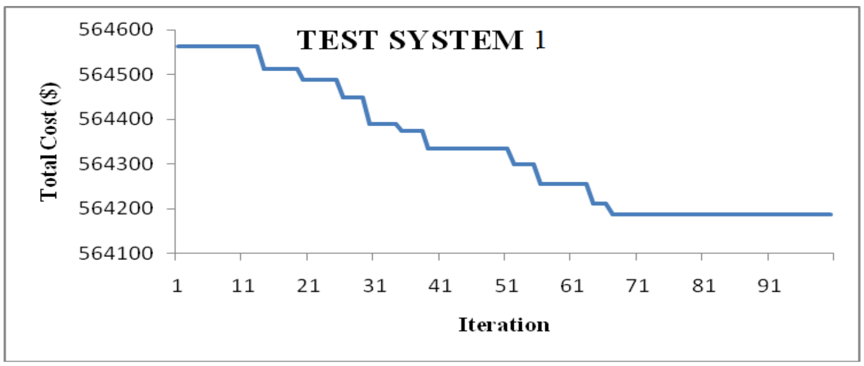

FIGURE 1. CONVERGENCE CURVE OF THE TEST SYSTEM 1

TABLE 2 Test Results Of 10-Unit System For Combined Uc And Emission Minimization

Hour	**Generation Schedule, MW**										**SC, $**	**Fuel cost, $**	**Emission, lb**
	P_1	**P_2**	**P_3**	**P_4**	**P_5**	**P_6**	**P_7**	**P_8**	**P_9**	**P_{10}**			
1	455	245	0	0	0	0	0	0	0	0	0	13683.08	956.36
2	455	295	0	0	0	0	0	0	0	0	0	14554.39	1055.02
3	455	265	0	130	0	0	0	0	0	0	560	16891.91	1077.33
4	455	235	130	130	0	0	0	0	0	0	550	19261.36	1249.78
5	455	285	130	130	0	0	0	0	0	0	0	20132.39	1343.76
6	455	360	130	130	25	0	0	0	0	0	900	22387.15	1549.72
7	455	410	130	130	25	0	0	0	0	0	0	23262.03	1704.26
8	455	455	130	130	30	0	0	0	0	0	0	24150.13	1863.08
9	455	455	130	130	85	20	25	0	0	0	860	27251.14	2183.28
10	455	455	130	130	140	55	25	10	0	0	60	30057.64	2599.12
11	455	455	130	130	162	73	25	10	10	0	60	31916.25	2945.22
12	455	455	130	130	162	80	25	43	10	10	60	33889.41	3229.37
13	455	455	130	130	140	55	25	10	0	0	0	30057.64	2599.12
14	455	455	130	130	85	20	25	0	0	0	0	27251.14	2183.28
15	455	455	130	130	30	0	0	0	0	0	0	24150.13	1863.08
16	455	310	130	130	25	0	0	0	0	0	0	21513.8	1424.18
17	455	260	130	130	25	0	0	0	0	0	0	20641.92	1318.57

18	455	360	130	130	25	0	0	0	0	0	0	22387.15	1549.72
19	455	455	130	130	30	0	0	0	0	0	0	24150.1	1863.08
20	455	455	130	130	140	55	25	10	0	0	490	30057.64	2599.12
21	455	455	130	130	85	20	25	0	0	0	0	27251.23	2191.28
22	455	315	130	130	25	20	25	0	0	0	0	23627.49	1718.82
23	455	245	0	130	25	20	25	0	0	0	0	19497.97	1346.83
24	455	275	0	0	25	20	25	0	0	0	0	17159.98	1319.6

TEST SYSTEM 2: 10 Unit Systems (Combined UC and Emission)

The application of WEO algorithm is extended to solve the combined UC and Emission problem in 10-unit system with 10% spinning reserve and without considering ramp rate constraint. The test system particulars are adopted from the literature. **Table 2** presents the 24h committed schedule for the 10-unit case and The dispatch of each generating unit shows that the generating capacity limit constraint as well as minimum up and down constraints is satisfied. As comparison shows, the best total cost obtained using WEO is **$ 1111845.35**, which is lesser than compared to RCGWO. **Figure 2** shows the convergence characteristics of the WEO which indicates that, initially, it is frequently changed, however, values are relatively small near to the final generation, which indicates a fine tuning of the searching space.

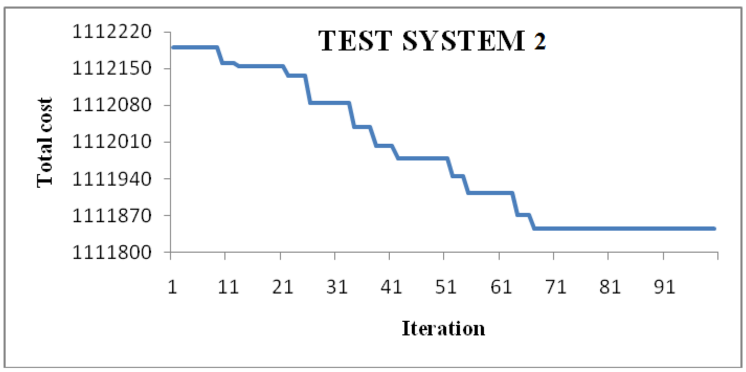

FIGURE 2 CONVERGENCE CURVE OF THE TEST SYSTEM 2

V. CONCLUSION

WEO algorithm is applied to solve the UC problems, UC with minimization of an emission and Combined UC and emission has been detailed. The performance of the proposed algorithm for solving UC is tested with the ten generating unit test system is adopted. Numerical simulation results demonstrate that this method is to be a promising alternative approach for solving UC in a power system. Finally the application of WEO algorithm is extended to solve the combined UC and Emission problem in 10-unit system with 10% spinning reserve and without considering ramp rate constraint. The obtained results are compared with RCGWO algorithm. The comparison clearly indicates that the proposed WEO based approach provides the most economical schedule for all cases.

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