ENHANCED MERIT ORDER AND AUGMENTED LAGRANGE HOPFIELD NETWORK FOR UNIT COMMITMENT

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Abstract – This paper presents an enhanced merit order (EMO) and augmented Lagrange Hopfield network (ALHN) for unit commitment (UC). The EMO method is a merit order based heuristic search for unit scheduling and ALHN is a continuous Hopfield network based on augmented Lagrange relaxation for economic dispatch problem. First, generating units are sorted in ascending average production cost and committed to fulfill load demand and spinning reserve requirements neglecting minimum up and down time constraints. Then, a heuristic search based algorithm is applied to satisfy minimum up and down time constraints, and modify start up cost from cold to hot if necessary. Finally, the ALHN is used to solve economic dispatch (ED). The proposed method is tested on systems ranging from 10 to 100 generating units and compared to augmented Hopfield network (AHN), conventional Lagrangian relaxation (LR), genetic algorithm (GA), evolutionary programming (EP), Lagrangian relaxation and genetic algorithm (LRGA), memetic algorithm (MA), Lagrangian relaxation and memetic algorithm (LRMA), genetic algorithm based on unit characteristic classification (GAUC), genetic algorithm based on unit characteristic classification and unit integration technique (GAUCUI), and extended priority list (EPL). The total production costs from the proposed method are less expensive and the computational times are vastly faster than the others, especially for the large number of generating units. For large-scale implementation, it is also tested on systems up to 1000 generating units with time horizon up to 168 hours. Test results indicate that the proposed method is very attractive and favorable due to substantial production costs savings and fast computational times.

Keywords: Merit order, augmented Lagrange Hopfield network, heuristic search, unit commitment.

NOMENCLATURE

ε	maximum tolerance for ALHN.
σ	slope of sigmoid function for continuous neurons;
α_i^t, α_λ^t	step sizes for updating of continuous and multiplier neurons respectively;
λ^t, β^t	Lagrangian multiplier and penalty factor in Lagrangian relaxation;
a_i, b_i, c_i	cost function coefficients of unit i, in \$/h, \$/MWh and \$/(MW)^{2}h, respectively;
DR_i	ramp down rate limit of unit i, MW/h;
Err_{max}	maximum error of ALHN for ED;
$F_i(P_i)$	quadratic cost function of unit i;
$g(U)$	sigmoid function of continuous neurons;
$g^{-1}(V)$	inverse sigmoid function for continuous neurons;
$h(U)$	sigmoid function of multiplier neurons;
K_{max}	maximum number of iterations of ALHN;
M_i	priority index for the unit i based on its average fuel cost, in \$/MWh;
N	total number of units;
P_D^t	system load demand at hour t, in MW;
$P_{i,max}$	maximum output power of unit i, in MW;
$P_{i,min}$	minimum output power of unit i, in MW;
P_i^t	generation output of unit i at hour t, in MW;
P_R^t	system spinning reserve at hour t, in MW;
r_i^t	unit reserve contribution at hour t, min[$P_{i,max}$ - P_i^t, UR_i], in MW;
$S_{i,c}$	cold start up cost of unit i, in \$;
$S_{i,h}$	hot start up cost of unit i, in \$;
S_i^t	start up cost of unit i at hour t, in \$;
T	time horizon for UC, in h;
$T_{i,cold}$	cold start hour of unit i, in h;
$T_{i,down}$	minimum down time of unit i, in h;
$T_{i,up}$	minimum up time of unit i, in h;
$T_{i,off}^t$	continuously off time of unit i, in h;
$T_{i,on}^t$	continuously on time of unit i, in h;
U_λ^t	total input of the multiplier neuron t;
U_i^t	status of unit i at hour t (on = 1, off = 0);
$U_{i,p}^t$	total input of the continuous neuron it;
UR_i	ramp up rate limit of unit i, MW/h;
V_λ^t	output of multiplier neuron t representing λ_t;
$V_\lambda^{t(0)}$	initial output of multiplier neuron t;
$V_{i,p}^{t(0)}$	initial output of continuous neuron it;
$V_{i,p}^t$	output of continuous neuron it representing P_{it};
x_i	fixed fraction of the maximum output of unit i;

1 INTRODUCTION

Unit commitment (UC) is used to schedule generators such that the total production cost of the system is minimized while maintaining sufficient spinning reserve and satisfying generator constraints. The UC problem is commonly a nonlinear, large-scale, mixed integer combinatorial problem. The exact solution of the UC problem can be obtained by complete enumeration of all feasible combinations generating of units, which is impossible for realistic power systems [1]. The needs for practical UC solutions encouraged the development of various methods providing sub-optimal but efficient scheduling for real sized power systems consisting of hundreds of generators.

The Lagrangian relaxation (LR) [2] method concentrated on finding an appropriate coordination technique for generating feasible primal solutions while minimizing the duality gap. The LR method was superior to the dynamic programming (DP) method [3] due to its higher quality solution and faster computational time. However, due to the non-convexity of the UC problem, optimality of the dual problem does not guarantee feasibility of the primal UC problem. The duality gap is used to estimate the quality of the suboptimal solution.

Recently, AI techniques have been widely applied to solve the UC problems such as neural networks [4-5], simulated annealing (SA) [6], tabu search (TS) [7], genetic algorithm (GA) [8-10], memetic algorithm (MA) [11], evolutionary programming (EP) [12]. However, SA, TS, GA, EP and MA required a considerable amount of computational time for large-scale problems. Hopfield network (HN) [4] was based on minimization of energy function to solve unit commitment problem with linear cost function and inequality constraints. However, the result obtained from this network is not better than that of LR. The main reason may be attributable to the inexact mapping of unit commitment to the neural network. Improvements of HN by combining of discrete and continuous HNs as augmented HN (AHN) were proposed in [5]. The AHN obtains better solution than the HN. However, the AHN still has "load offset", that is the power balance is not satisfied. Thus, it needs an offset for this constraint. To reduce the search space in large-scale problems and obtain better solutions, hybrid systems are used such as Lagrangian relaxation and genetic algorithm (LRGA) [13], Lagrangian relaxation and memetic algorithm (LRMA) [11], evolutionary programming based tabu search (EPBTS) [14], and neural based tabu search (NBTS) [15]. The hybrid systems have shown that they are more efficient than the single methods in terms of cost and computational time.

This paper proposes a simple and effective method consists of enhanced merit order (EMO) for unit scheduling and augmented Lagrange Hopfield network (ALHN) for economic dispatch. The EMO is a merit order based heuristic search and ALHN is a continuous Hopfield neural network based on augmented Lagrange relaxation. First, the generating units are sorted in ascending list based on production cost and committed to meet the requirement of load demand and spinning reserve neglecting minimum up and down time constraints. Then, a heuristic search based algorithm is applied to satisfy the minimum up and down time constraints as well as modify start up cost from cold to hot if necessary. Finally, ALHN is applied for economic dispatch (ED) using the obtained unit scheduling. The total production costs and computing times of the proposed method are compared to augmented Hopfield network (AHN) [5], conventional Lagrangian relaxation (LR) [8], genetic algorithm (GA) [8], evolutionary programming (EP) [12], Lagrangian relaxation and genetic algorithm (LRGA) [13], memetic algorithm (MA) [11], Lagrangian relaxation and memetic algorithm (LRMA) [11], genetic algorithm based on unit characteristic classification (GAUC) [9], genetic algorithm based on unit characteristic classification and unit integration technique (GAUCUI) [10], and extended priority list (EPL) [20]. Furthermore, the proposed method has also been tested on systems up to 1000 generating units with time horizon up to 168 hours.

The organization for the rest of the paper is as follows. Section 2 describes the UC problem formulation. The enhanced merit order for unit scheduling is addressed in Section 3. The augmented Lagrange Hopfield for economic dispatch is followed in Section 4. Numerical results are shown in Section 5. Finally conclusion is given.

2 UNIT COMMITMENT PROBLEM FORMULATION

The objective of the UC problem is to minimize

$$Min\sum_{t=1}^{T}\sum_{i=1}^{N}\left[a_i + b_i P_i^t + c_i (P_i^t)^2 + S_i^t\left(1-U_i^{t-1}\right)\right]U_i^t \quad (1)$$

subject to

(a) Power balance constraints

$$P_D^t - \sum_{i=1}^{N} P_i^t U_i^t = 0 \quad (2)$$

(b) Spinning reserve constraint

$$P_D^t + P_R^t - \sum_{i=1}^{N} P_{i,\max} U_i^t \le 0 \quad (3)$$

(c) Generation limit constraints

$$P_{i,\min} U_i^t \le P_i^t \le P_{i,\max} U_i^t \quad (4)$$

(d) Minimum up and down time constraints

$$U_i^t = \begin{cases} 1 & \text{if } T_{i,on}^t < T_{i,up} \\ 0 & \text{if } T_{i,off}^t < T_{i,down} \\ 0 \text{ or } 1 & \text{otherwise} \end{cases} \quad (5)$$

(e) Start up cost

$$S_i^t = \begin{cases} S_{i,h} & \text{if } T_{i,down} \le T_{i,off}^t \le T_{i,cold} + T_{i,down} \\ S_{i,c} & \text{if } T_{i,off}^t > T_{i,cold} + T_{i,down} \end{cases} \quad (6)$$

3 ENHANCED MERIT ORDER FOR UNIT SCHEDULING

The proposed EMO consists of two stages. In the first stage, the merit order is used to commit units to satisfy load demand and spinning reserve neglecting minimum up and down time constraints. In the second stage, a heuristic search based algorithm is applied to merit order based unit schedule to satisfy the minimum up and down time constraints and modify start up costs from cold to hot if possible. Using the unit scheduling by EMO, ALHN is used to solve economic dispatch to obtain the final UC schedule in Section 4.

3.1 Merit order for unit scheduling

The merit order is based on fuel cost obtained based on the average fuel cost of each unit operating at a certain fixed fraction of maximum output [16]. The merit order is defined as follows:

$$M_i = \left.\frac{F_i(P_i)}{P_i}\right|_{x_i P_{i,\max}} \quad (7)$$

In this paper, the value of x_i is chosen as follows:

$$x_i = \frac{1}{2}\left(1 + \frac{P_{i,\min}}{P_{i,\max}}\right) \quad (8)$$

Procedure of merit order for committing units is as follows:

Step 1: Calculate values of M_i in (7).
Step 2: Sort units in ascending order of M_i.
Step 3: Set t = 1.
Step 4: Set i = 1.
Step 5: If $\sum_{n=1}^{i} P_{n,\max} < P_D^t + P_R^t$ and $i < N$, $i = i + 1$ and repeat this step. Otherwise, go to Step 6.
Step 6: If $t < T$, $t = t + 1$ and return to Step 4. Otherwise, stop.

3.2 Heuristic search based algorithm

After obtaining the merit order based unit schedule, the minimum up and down time constraints may not be satisfied. A heuristic search based algorithm is conducted to relieve the violations.

To check for violations, on and off times of units are determined in advance. The on/off times at hour t are calculated according to the previous times as follows:

$$\begin{aligned} T_{i,on}^t &= T_{i,on}^{t-1} + 1 \qquad \text{if } U_i^t = 1 \\ T_{i,off}^t &= T_{i,off}^{t-1} + 1 \qquad \text{if } U_i^t = 0 \end{aligned} \tag{9}$$

1) Minimum up and down times repairing

Minimum up time of units is usually violated at peak load where the peak load hours are shorter than minimum up time, "hills" exist. Similarly, minimum down time is usually violated at low-level load where low-level load hours are shorter than minimum down times of units, and "valleys" exist. The algorithm will check by banking "hills" and filling "valleys". Examples are shown in Figure 1.

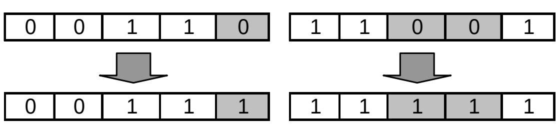

Figure 1: Repairing of minimum up and down time.

Procedure of minimum up and down times repairing is follows:

Step 1: Calculate continuous on and off times of all units using (9);
Step 2: Set t = 1.
Step 3: Set i = 1.
Step 4: If $U_i^t = 0$ and $U_i^{t-1} = 1$ and $T_{i,on}^{t-1} < T_{i,up}$, $U_i^t = 1$. If $U_i^t = 0$ and $U_i^{t-1} = 1$ and $T_{i,off}^{t+T_{i,down}-1} < T_{i,down}$, $U_i^t = 1$.
Step 5: Update the on/off status for the unit i in (9).
Step 6: If $i < N$, $i = i + 1$ and return to Step 4.
Step 7: If t < T, t = t + 1 and return to Step 3. Otherwise, stop.

2) Modification of start up costs

The algorithm considers the modification of start up costs from cold to hot if the cost savings from the modification is higher than maintaining cost for the unit during the changed interval. The proposed algorithm only checks one hour ahead because two or more hours ahead considered will lead to maintaining cost higher than cost savings from start up. Figure 2 shows an example for modification of start up in one hour ahead.

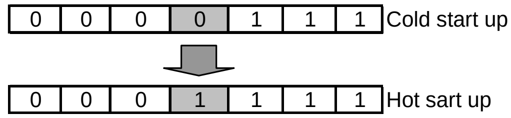

Figure 2: Modification from cold to hot start up.

Procedure for modification of start up costs is:

Step 1: Set t = 1.
Step 2: Set i = 1.
Step 3: If $U_i^t = 1$ and $U_i^{t-1} = 0$ and $T_{i,off}^{t-1} = T_{i,off}^t + T_{i,cold} + 1$ and saving from start up higher than maintaining cost in one hour, then $U_i^{t-1} = 1$.
Step 4: If $i < N$, $i = i + 1$ and return to Step 3.
Step 5: If $t < T$, $t = t + 1$ and return to Step 2. Otherwise, stop.

3) Decommitment of excessive units

Excessive units are the consequence of minimum up and down time constraints, leading to excessive spinning reserve. The algorithm looks for units that can be decommitted without violating constraints starting from the units with highest values of M_i until there is no unit that can be decommitted. An example is shown in Figure 3.

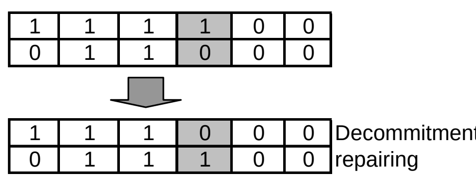

Figure 3: Decommitment of excessive spinning reserve unit due to minimum up time constraints.

Procedure for decommitment of excessive units is as follows

Step 1: Set t = 1.
Step 2: Set i = 1.
Step 3: If unit i can be decommitted without violations, put the unit into excessive list.
Step 4: If $i < N$, $i = i + 1$ and return to Step 3. Otherwise, go to Step 5.
Step 5: If the excessive list is empty, go to Step 7.
Step 6: Decommit the unit with highest M_i in the excessive list and eliminate this unit out of the list. Check for the next unit in the list if it can be decommitted without violating spinning reserve. Repeat this step until no unit can be decommitted.
Step 7: If $t < T$, $t = t + 1$ and return to Step 2. Otherwise, stop.

4 AUGMENTED LAGRANGE HOPFIELD NETWORK FOR ECONOMIC DISPATCH

The ALHN is based on the energy function of augmented Lagrangian relaxation and Hopfield techniques. The proposed ALHN is augmented by Hopfield term [17] and solved by gradient descent method. Moreover, the sigmoid function used for continuous neurons of the ALHN is from [18].

4.1 Formulation of ED problem

The ED problem is formulated based on the result of the unit-scheduling problem. Once the unit scheduling solution is determined, start-up costs are determined and spinning reserve, minimum up and down time constraints are also satisfied. The objective of the ED problem is to minimize the operation cost neglecting start up costs and satisfy power balance constraints and generators limits.

The objective to be minimized is

$$Min\sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i^{'}+b_i^{'}P_i^t+c_i^{'}(P_i^t)^2\right) \tag{10}$$

subject to

(a) power balance constraint

$$P_D^t-\sum_{i=1}^{N}P_i^t=0 \tag{11}$$

(b) generation limit constraints

$$P_{i,\min}^{'}\le P_i^t\le P_{i,\max}^{'} \tag{12}$$

where $a_i^{'}=a_iU_i^t$, $b_i^{'}=b_iU_i^t$, $c_i^{'}=c_iU_i^t$, $P_{i,\max}^{'}=P_{i,\max}U_i^t$, $P_{i,\min}^{'}=P_{i,\min}U_i^t$, and U_i^t has been determined from the EMO for the unit scheduling.

4.2 The ALHN for the ED problem

Augmented Lagrangian relaxation for the problem is:

$$\begin{aligned}L=&\sum_{t=1}^{T}\sum_{i=1}^{N}\left(a_i^{'}+b_i^{'}P_i^t+c_i^{'}(P_i^t)^2\right)\\&+\sum_{t=1}^{T}\left[\lambda^t\left(P_D^t-\sum_{i=1}^{N}P_i^t\right)+\frac{1}{2}\beta^t\left(P_D^t-\sum_{i=1}^{N}P_i^t\right)^2\right]\end{aligned} \tag{13}$$

To represent the problem in form of augmented Lagrange Hopfield network, *N*x*T* continuous neurons for output power and *T* multiplier neurons for Lagrange multipliers are required. The energy function for ALHN is formulated as follows:

$$\begin{aligned}E=&\sum_{t=1}^{T}\sum_{i=1}^{N}\left[a_i^{'}+b_i^{'}V_{i,p}^t+c_i^{'}\left(V_{i,p}^t\right)^2\right]\\&+\sum_{t=1}^{T}\left[V_\lambda^t\left(P_D^t-\sum_{i=1}^{N}V_{i,p}^t\right)+\frac{1}{2}\beta^t\left(P_D^t-\sum_{i=1}^{N}V_{i,p}^t\right)^2\right]\\&+\sum_{t=1}^{T}\sum_{i=1}^{N}\int_0^{V_{i,p}^t}g^{-1}(V)dV\end{aligned} \tag{14}$$

where the sum of integral terms are Hopfield terms where their global effect is a displacement of solutions toward the interior of the state space [17].

The dynamics of ALHN for updating neuron inputs are derived as follows:

$$\frac{dU_{i,p}^t}{dt}=-\frac{\partial E}{\partial V_{i,p}^t}=-\left\{\begin{array}{l}b_i^{'}+2c_i^{'}V_{i,p}^t\\-\left[V_\lambda^t+\beta^t\left(P_D^t-\sum_{i=1}^{N}V_{i,p}^t\right)\right]+U_{i,p}^t\end{array}\right\} \tag{15}$$

$$\frac{dU_\lambda^t}{dt}=+\frac{\partial E}{\partial V_\lambda^t}=P_D^t-\sum_{i=1}^{N}V_{i,p}^t \tag{16}$$

The algorithm for updating neurons is as follows:

$$U_{i,p}^{t(k)}=U_{i,p}^{t(k-1)}-\alpha_i^t\frac{\partial E}{\partial V_{i,p}^t} \tag{17}$$

$$U_\lambda^{t(k)}=U_\lambda^{t(k-1)}+\alpha_\lambda^t\frac{\partial E}{\partial V_\lambda^t} \tag{18}$$

The outputs of neurons, which represent output power of units, are limited by maximum and minimum values calculated by a sigmoid function [18]:

$$V_{i,p}^t=g(U_{i,p}^t)=\left(P_{i,\max}^{'}-P_{i,\min}^{'}\right)\left(\frac{1+\tanh(\sigma U_{i,p}^t)}{2}\right)+P_{i,\min}^{'} \tag{19}$$

where σ is known as slope that determines the shape of the sigmoid function.

Since multiplier neurons are unconstrained outputs, the outputs are defined as below:

$$V_\lambda^t=h(U_\lambda^t)=U_\lambda^t \tag{20}$$

1) Initialization

The algorithm requires initial conditions for the inputs of neurons. For the continuous neurons, the inputs are initiated by "mean distribution" [19], e.g. the initial value of each unit is proportion to its maximum contribution in total load demand.

$$V_{i,p}^{t(0)}=\frac{P_{i,\max}^{'}}{\sum_{i=1}^{N}P_{i,\max}^{'}}P_D^t \tag{21}$$

and the multiplier neurons are initialized by mean value according to simplified $\partial E/\partial V_{i,p}^t=0$, in which β^t and $U_{i,p}^t$ are neglected, the mean value of $V_\lambda^{t(0)}$ is determined:

$$V_\lambda^{t(0)}=\frac{\sum_{i=1}^{N}\left(b_i^{'}+2c_i^{'}V_{i,p}^{t(0)}\right)}{N} \tag{22}$$

2) Selection of parameters

The proper parameter selection will guarantee rapid convergence. By experiment, the values of σ and β^t are fixed at 100 and 0.001 for all test systems, respectively. The values of α_i^t and α_λ^t will vary depending on the data being processed.

3) Termination criteria

In the proposed ALHN, the algorithm will be terminated when either the maximum error Err_{max} from power balance constraint (11) and iterative errors of neurons is lower than a pre-specified threshold ε or maximum number of iterations K_{max} is reached.

4) Calculation of total production cost

Total production cost includes total operational cost from economic dispatch problem and total start up cost from unit scheduling problem.

Followings are the procedure of the ALHN for ED:

Step 1: Select parameters for the ALHN consisting of σ, α_i^t, α_λ^t, and β^t.

Step 2: Initialize continuous and multiplier neurons by using (22) and (22).

Step 3: Set k = 1.

Step 4: Calculate dynamics of neurons by using (15) and (16).

Step 5: Update inputs of neurons using (17) and (18).

Step 6: Calculate outputs of neurons by using (19) and (20).

Step 7: If $Err_{max} > \varepsilon$ and $k < K_{max}$, $k = k + 1$ and return to Step 4. Otherwise, go to Step 8.

Step 8: Calculate total production cost by summing total start up cost and total operational cost, and stop.

Many methods can be used to solve the economic dispatch sub-problem. In this paper, the ALHN is applied to solve economic dispatch due to its effectiveness [21]. The ALHN can efficiently handle more variables and constraints by its sigmoid function and using Lagrange relaxation as its energy function. Moreover, the ALHN is a recurrent neural network with parallel processing, so it is fast enough to solve time dependent economic dispatch problems, especially the very large-scale ones.

5 NUMERICAL RESULTS

The proposed method is tested on systems in [5] and [8]. The maximum error of the ALHN is set to 10^{-3}. Algorithm of the method is coded in MATLAB and run on 1.1GHz Celeron 128MB of RAM PC.

5.1 17-unit system

The system described in [5] has 17 units scheduled in a horizon of 24 hours. The system reserve is set at 100MW. Merit order for this system is in Table 1.

Unit	1	2	3	4	5	6
Priority index	1	2	4	5	3	7
Unit	7	8	9	10	11	12
Priority index	11	14	10	6	16	15
Unit	13	14	15	16	17	
Priority index	8	9	17	13	12	

Table 1: Merit order for 17-unit system.

Method	Cost (£)	Relative to LR (%)	CPU time (sec)
LR [5]	1,033,901	0	3
AHN [5]	1,027,380	-0.63	16
LRAHN [5]	1,026,709	-0.70	8
EMO-ALHN	1,016,062	-1.73	0.47

Table 2: Comparison of total production cost and CPU time for 17 units system.

Result from the proposed method for this system is compared to AHN in terms of total production cost and computational time. Table 2 shows the result obtained by the proposed method compared to LR, AHN and LRAHN. The total production cost from the proposed method is less expensive than LR [5] 1.73%, AHN [5] 1.10% and LRAHN [5] 1.04%. Computational time from the proposed method is sufficiently small. Note the CPU time reported in [5] is on a Pentium Pro™ 200MHz machine.

In this case, the solution by the LR is obtained from [5], which is only used for result comparison in this paper. Moreover, this paper does not focus on LR for the UC problem. Therefore, the detail solution of the LR is not described.

5.2 Systems up to 1000 units

The system in [8] has 10 units and is scheduled over 24 hours. The spinning reserve requirement is set to be 10% of total load demand. For the systems of 20, 40, 60, 80, 100, 200, 500 and 1000 units, the basic 10 units system is duplicated and total load demands are adjusted in proportion to the system size. For schedule time up to 168 hours, the basic 24 hours schedule is extended. Merit order for this system is in Table 3.

Results from the proposed method up to 100 units are compared to other methods listed in Tables 4 and 5. In terms of total production costs, the proposed method is less expensive than other methods except LRGA [13] for 20 and 40 units systems.

Unit	1	2	3	4	5
Priority order	1	2	5	4	3
Unit	6	7	8	9	10
Priority order	6	7	8	9	10

Table 3: Merit order for 10 units system.

For the CPU times in this case, it may not be directly compared due to different computers used. The CPU times of GA [8] and EP [12] methods were obtained from HP Apollo 720 workstation and HP C160 workstation, respectively. The hardware of computer used in MA and LRMA in [11] was roughly 7 times faster than that used in GA [8]. The computers used for LRGA [11] and EPL [20] were 486DX2-66 PC and Intel Pentium 4 CPU 1.5GHz, respectively. There was no report of computers used in GAUC [9] and GAUCUI [10]. Since the hardware of the computer used in this study is not much faster than other methods, the CPU times of EMO-ALHN are extremely faster than the others and increases slightly with the system size.

Although the proposed EMO looks similar to the EPL, the priority index and heuristic search used are different. In the EPL, the larger unit of output power could have a high priority list, which may lead to inexact priority order. Moreover, the complicated heuristics in the EPL applied to plurality of initial solutions consume time considerably. Therefore, the results from the EPL are less efficient than the proposed method in terms of cost and computational time, especially for large-scale problems.

No. of units	10	20	40	60	80	100
LR [8]	565,825	1,130,660	2,258,503	3,394,966	4,526,022	5,657,277
MA [11]	565,827	1,127,254	2,252,937	3,388,676	4,501,449	5,640,543
GA [8]	565,825	1,126,243	2,251,911	3,376,625	4,504,933	5,627,437
GAUC [9]	563,977	1,125,516	2,249,715	3,375,065	4,505,614	5,626,514
EP [12]	564,551	1,125,494	2,249,093	3,371,611	4,489,479	5,623,885
LRMA [11]	566,686	1,128,192	2,249,589	3,370,595	4,494,214	5,616,314
LRGA [13]	564,800	1,122,622	2,242,178	3,371,079	4,501,844	5,613,127
GAUCUI [10]	-	-	2,247,336	3,367,637	4,491,509	5,610,855
EPL [20]	563,977	1,124,369	2,246,508	3,366,210	4,489,322	5,608,440
EMO-ALHN	563,977	1,123,951	2,246,269	3,364,856	4,488,067	5,606,910

Table 4: Comparison of total production costs (in $) for systems up to 100 units.

No. of units	10	20	40	60	80	100
MA [11]	84	287	1,063	2,272	5,145	10,463
GA [8]	221	733	2,697	5,840	10,036	15,733
GAUC [9]	85	225	614	1,085	1,975	3,547
EP [12]	100	340	1,176	2,267	3,584	6,120
LRMA [11]	61	113	217	576	664	1,338
LRGA [13]	518	1,147	2,165	2,414	3,383	4,045
GAUCUI [10]	-	-	29	42	60	75
EPL [20]	0.72	2.97	11.90	23.00	44.40	64.50
EMO-ALHN	0.19	0.30	0.32	0.42	0.66	1.22

Table 5: Computational times (in sec) comparison for various systems up to 100 units.

The cost reduction effectiveness of modification of start up costs and decommitment of excessive units are also shown in Table 6, in which the cost difference is the difference between the total costs without modification of start up costs or decommitment of excessive units and the final total costs.

No. of unit	W/O modification of start up costs		W/o decommitment of excessive units	
	Total cost ($)	Cost difference ($)	Total cost ($)	Cost difference ($)
10	563,977	0	564,906	929
20	1,124,325	374	1,126,855	2,904
40	2,246,824	555	2,251,839	5,570
60	3,366,195	1,339	3,374,266	9,410
80	4,489,356	1,289	4,499,908	11,841
100	5,609,172	2,262	5,622,781	15,871

Table 6: Cost difference between the total costs without modification of start up costs or decommitment of excessive units and the final total costs.

The proposed EMO-ALHN is also tested on systems up to 1000 units and time horizon up to 168 hours as shown in Table 7. The CPU time reported increases linearly with the system size and time horizon, which is very practical for large-scale implementation.

Although several other references on UC considering ramp rates and start-up costs are available on the technical literature, ramp rate constraints and time-dependence start up cost are not taken into account in this paper since the purpose is to compare the solutions with the previous work in [8], [9], [10], [11], [12], [13] and [20]. However, the framework used allows considering those constraints for both unit basis and system basis to approach more general problem [22]. On the system basis, the spinning reserve constraint (3) can be modified as

$$P_R^t - \sum_{i=1}^{N} r_i^t U_i^t \le 0 \tag{23}$$

Time horizon (h)	No. of units	Cost ($)	CPU time (sec)
24	200	11,210,965	1.95
	500	28,020,744	6.55
	1000	56,033,920	20.12
168	200	78,519,542	10.92
	500	196,256,408	51.80
	1000	392,474,117	150.30

Table 7: Demonstration of the EMO-ALH up to 1000 unit system and time horizon up to 168 hours.

On the unit basis, the generation limit constraint (4), including the generator operating limits and on/off line minimum level constraint, is modified as

$$P_{i,low}^t U_i^t \le P_i^t \le P_{i,high}^t U_i^t,\ i = 1, \ldots, N \tag{24}$$

where

$$P_{i,high}^t = \begin{cases} \min[P_{i,\max}, P_i^{t-1} + UR_i] & \text{if } U_i^t = U_i^{t-1} = 1 \\ P_{i,\min} & \text{if } U_i^t = 1, U_i^{t-1} = 0 \text{ or if } U_i^t = 1, U_i^{t+1} = 0 \end{cases} \tag{25}$$

$$P_{i,low}^t = \begin{cases} \max[P_{i,\min}, P_i^{t-1} - DR_i] & \text{if } U_i^t = U_i^{t-1} = 1 \\ P_{i,\min} & \text{if } U_i^t = 1, U_i^{t-1} = 0 \text{ or } U_i^t = 1, U_i^{t+1} = 0 \end{cases} \quad (26)$$

To solve the ramp rate constrained UC, the EMO-ALHN has to handle the modified spinning reserve and generation limit constraints.

6 CONCLUSION

This paper proposes a simple and efficient method based on EMO and ALHN for unit commitment. The total production costs of the proposed method are less expensive than other methods reported in literature on various systems. The highlighted advantage of the proposed method is that the computational times are extremely faster than others and slightly increase with the system size, which is very favorable for large scale implementation.

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