JKAU: Eng. Sci., **Vol. 23** No. 1, pp: 21-37 (2012 A.D. /1433 A.H.)

DOI: 10.4197 / Eng. 23-1.2

An Application of Particle Swarm Optimization (PSO) to Dynamic Unit Commitment Problem for the Western Area of Saudi Arabia

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*Abstract***.** Unit commitment (UC) in power systems typically involves properly scheduling the on/off states as well as the real power outputs (economic dispatch) of all resources (generators/units) in the system. In addition to fulfill a large number of system constraints, the UC meets forecasted load demand calculated in advance, plus the spinning reserve requirement at each time interval, such that the total cost (mainly fuel cost) is minimum. In this paper particle swarm optimization (PSO) is applied to minimize cost, emission or cost-emission of the Unit Commitment problem. For unit commitment both cost and emission are considered. Actually cost and emission are trade-off. If cost increases, emission decreases and vice-versa. Real power is forecasted and used in the Unit Commitment of the Western Area of Saudi Arabia. The total cost for generation for 24 h is 4332905$ and the emission is 193479 ton.

Nomenclature and Acronyms

The following notations are used in this paper.

$c\text{-}cost_i$	:	Cold start cost of unit i
$c\text{-}s\text{-}hour_i$	:	Cold start hour of unit i
$D(t)$	:	Load demand at time t
ED	:	Economic dispatch
$FC()$	:	Fuel cost function
$h\text{-}cost_i$	:	Hot start cost of unit i
H	:	Scheduling period
$I_i(t)$	:	On/off status of unit i at hour t
MU_i/MD_i	:	Minimum up/down time of unit i
N	:	Number of units
$P_i(t)$	:	Output power of unit i at time t

P_i^{max}	:	Maximum output limit of unit i
Pi^{min}	:	Minimum output limit of unit i
$P_i^{\max}(t)$	:	Maximum output power of unit i at time t considering ramp rate
$P_i^{min}(t)$	:	Minimum output power of unit i at time t considering ramp rate
P_v	:	Capacity of each vehicle
RUR_i	:	Ramp up rate of unit i
RDR_i	:	Ramp down rate of unit i
$R(t)$	:	System reserve requirement at hour t
$SC_i()$	:	Start-up cost function of unit i
TC	:	Total cost
$U(0,1)$		Uniform distribution between 0 and 1
$X_i^{on}(t)$	:	Duration of continuously on of unit i at time t
$X_i^{off}(t)$	:	Duration of continuously off of unit i at time t
Z_i	:	Number of prohibited zones of unit i

1. Introduction

The power and energy industry – in terms of (a) economic importance and (b) environmental impact – is one of the most important sectors in the world since nearly every aspect of industrial productivity and daily life are dependent on electricity. The alarming rate, at which global energy reserves are depleting, is a major worldwide concern at economic, environmental, industrial and societal levels. The power and energy industry represents a major portion of global emission, which is responsible for 40% of the global CO_2 production followed by the transportation sector (24%). Climate change caused by greenhouse gas (GHG) emissions is now widely accepted as a real condition that has potentially serious consequences for human society and industries need to factor this into their strategic plans. So economic and environment friendly modern planning is essential.

A bibliographical survey on UC methods reveals that various numerical optimization techniques have been employed to approach the UC problem since the last three decades. Among these methods, priority list (PL) methods [1-3] are very fast, however they are highly heuristic and generate schedules with relatively higher operation cost. Branch-and-bound (BB) methods [4-7] have the danger of a deficiency of storage capacity and increasing the calculation time enormously for a large-scale UC problem. Lagrangian relaxation (LR) methods [8-12] concentrate on finding an appropriate co-ordination technique for generating feasible primal solutions, while minimizing the duality gap. The main problem with an LR method is the difficulty encountered in obtaining feasible solutions. The meta-heuristic methods [13-38] are iterative techniques that can search not only local optimal solutions, but also a global optimal solution depending on problem domain and execution time limit. In the meta-heuristic methods, the techniques frequently applied to the UC problem are genetic algorithm (GA), tabu search (TS), evolutionary programming (EP), simulated annealing (SA), *etc*. They are general-purpose searching techniques based on principles inspired from the genetic and evolution mechanisms observed in natural systems and populations of living beings. These methods have the advantage of searching the solution space more thoroughly. However, difficulties are their sensitivity to the choice of parameters, balance between local and global searching abilities, proper information sharing and conveying mechanism, converging to local minima, convergence rate, constraint management and so on. Fuzzy UC models are also available in [39-44]. However, they are imprecise and need sufficient previous statistics to model the imprecision.

Vehicle-to-grid (V2G) technology has drawn great interest in recent years. V2G researchers have mainly concentrated on interconnection of energy storage of electric vehicles (EVs) and grid [45-51]. Their goals are to educate about the environmental and economic benefits of V2G and enhance the product market. However, success of V2G researches greatly depends on the efficient scheduling of EVs in limited and restricted parking lots, *i.e.*, maximization of profit. As the number of EVs in V2G is much higher than small units of existing systems, UC with V2G is more complex than typical UC for only thermal units. UC with V2G makes a bridge between UC and V2G research areas. It extends the area of unit commitment bringing in the V2G technology and making it a success. The authors have reported unit commitment with V2G in [52-56], where the focus is mainly on cost, emission and cost-emission optimizations..

Regarding optimization, particle swarm optimization (PSO) is simple, easy to implement, promising, and it requires less computation time and memory, though it requires an extra transformation for solving discrete optimization problems [57-58]. Thus in this paper PSO is applied to minimize cost, emission or cost-emission of the UC problem for the western area of Saudi Arabia.

2. Economic AND/OR Environment Friendly Unit Commitment

An economic and/or environment friendly unit commitment (EEFUC) problem involves in cost and/or emissions reductions of power systems in multi-dimensional complex search space. Costs and emissions come from thermal units. Emission can also be used as a constraint to limit the emission up to a certain level. Depending on system operators, economic and/or environment friendly unit commitment has one of the three objectives: Cost optimization, emission optimization or cost-emission optimization subject to equality-inequality constraints.

Usually large cheap units are used to satisfy base load demand of a system. Most of the time, large units are therefore on and they have slower ramp rates. On the other hand, small units have relatively faster ramp rates. In unit commitment problem, main challenge is to properly schedule small expensive units to handle uncertain, fluctuating and peak loads. Profit, spinning reserve, reliability of power systems vary on scheduling optimization quality.

Cost, emission or cost-emission reduction refer to combined reductions in the costs of fuel, emission or both cost and emission. The objective function of UC for cost, emission or cost-emission is

$$\min_{I_i(t),P_i(t)} \left\{ \begin{array}{l} \sum\limits_{i=1}^{N} \sum\limits_{t=1}^{H} [(FC_i(P_i(t)) + SC_i(1 - I_i(t-1)))I_c + \\ W_i(\varphi_i EC_i(P_i(t)))I_e]I_i(t) \end{array} \right\} \tag{1}$$

$$W_i = \frac{FC_i(P_i^{\max})}{EC_i(P_i^{\max})} \tag{2}$$

subject to constraints. Decision variables are on/off states, $I_i(t)$ of thermal units and corresponding dispatch $P_i(t)$, where i =1,2,…,N and t =1,2,…,H (N=number of thermal units and H=scheduling period). Power $P_i(t)$ of all the units i=1,2,…,N are calculated in ED for the schedule $I_i(t)$.

For weighted aggregation implementation of UC, a single fitness value from both cost and emission objectives is calculated in eq. (1). W_i are the emission penalty factors of units i, which are calculated in equation (2). Actually W_i are converters here that convert emissions to equivalent costs. Weight factors I_c and I_e are also used to include (1) or exclude (0) cost and emission in the fitness function for increasing flexibility of the system. If I_c =1 and I_e=0, equation (1) is a single objective cost minimization problem. Similarly if I_c=0 and I_e=1, equation (1) is a single objective emission minimization problem. However, both I_c and I_e are 1 to minimize both cost and emission. Different weights (*e.g.*, $0 < I < 1$) may also be used to assign different precedence of cost and emission in the system.

Any new type of cost may be included or any existing type of cost may be excluded from the objective function according to the system operators' demand in the deregulated market. Different weights may also be assigned to different types of cost depending on their relative importance in the changing environment.

Fuel Cost

Fuel cost of a thermal unit is expressed as a second order function of each unit output as follow:

$$FC_i(P_i(t)) = a_i + b_i P_i(t) + c_i P_i^2(t) \tag{3}$$

where a_i , b_i and c_i are positive fuel cost coefficients of unit i. Higher order coefficients are ignored for simplicity.

Emission from Thermal Unit

Typically emission is expressed as polynomial function and order depends on desired accuracy. Quadratic function is considered for the emission curve as follows:

$$EC_i(P_i(t)) = \alpha_i + \beta_i P_i(t) + \gamma_i P_i^2(t) \tag{4}$$

where α_i, β_i and γ_i are emission coefficients of unit i, and $P_i(t)$ is output level of unit i at time t. Higher order coefficients are ignored for simplicity.

Start-up Cost

The start-up cost for restarting a decommitted thermal unit, which is related to the temperature of the boiler, is included in the model. If the unit is cold which means that it has been shut down for a long time, it is necessary to consume more fuel to warm up the boiler. If the unit has been decommitted for a short while (which satisfies the minimum down time), less energy will be needed to restart the unit. In this paper, a step function of time-dependent start-up cost is simplified using transition hour (H_i^{off}) from hot to cold start which is defined in Ref. [1] and [2]. Start-up cost will be high cold cost (*c-cost$_i$*) when down time duration (X_i^{off}) exceeds cold start hour (*c-s-hour$_i$*) in excess of minimum down time (*MD$_i$*) and will be low hot cost (*h-cost$_i$*) when down time duration does not exceed *c-s-hour$_i$* in excess of minimum down time as follows:

$$SC_i(t) = \begin{cases} h-\cos t_i : MD_i \leq X_i^{off}(t) \leq H_i^{off} \\ c-\cos t_i : X_i^{off}(t) \geq H_i^{off} \end{cases} \tag{5}$$

$$H_i^{off} = MD_i + c - s - hour_i \tag{6}$$

Shut-down Cost

Shut-down cost is constant and the typical value is zero in standard systems.

Constraints

The constraints that must be satisfied during the optimization process are as follows.

System Power Balance

The generated power from all the committed units and gridable vehicles must satisfy the load demand and the system losses, which is defined as

$$\sum_{t=1}^{N} I_i(t)P_i(t) = D(t) + Losses\ . \tag{7}$$

Spinning Reserve

To maintain system reliability, adequate spinning reserves are required.

$$\sum_{t=1}^{N} I_i(t)P_i^{\max}(t) \geq D(t) + losses + R(t). \tag{8}$$

Generation Limits

Each unit has generation range, which is represented as

$$P_i^{\min} \le P_i(t) \le P_i^{\max} . \tag{9}$$

Minimum up/down Time

Once a unit is committed/decommitted, there is a predefined minimum time before it can be decommitted/committed again.

$$\left.\begin{aligned} &(1 - I_i(t+1))MU_i \le X_i^{on}(t), \ \text{ iff } I_i(t) = 1 \\ &I_i(t+1)MD_i \le X_i^{off}(t), \ \text{ iff } I_i(t) = 0 \end{aligned}\right\}. \tag{10}$$

Ramp Rate

For each unit, output is limited by ramp up/down rate at each hour as follow:

$$\left.\begin{aligned} &P_i^{\min}(t) \le P_i(t) \le P_i^{\max}(t) \\ &P_i^{\min}(t) = \max(P_i(t-1) - RDR_i, P_i^{\min}) \\ &P_i^{\max}(t) = \min(P_i(t-1) - RUR_i, P_i^{\max}) \end{aligned}\right\}. \tag{11}$$

Prohibited Operating Zone

In practical operation, the generation output $P_i(t)$ of unit i at time t must avoid unit operation in the prohibited zones. The feasible operating zones of unit i can be described as follows:

$$P_i(t) \in \begin{cases} P_i^{\min} \le P_i(t) \le P_{i,1}^{l} \\ P_{i,z-1}^{u} \le P_i(t) \le P_{i,z}^{l}, \ z = 2,3,\ldots,Z_i \\ P_{i,Z_i}^{u} \le P_i(t) \le P_i^{\max} \end{cases} \tag{12}$$

where $P_{i,z}^{l}$ and $P_{i,z}^{u}$ are lower and upper bounds of the z-th prohibited zone of unit i, and Z_i is the total number of prohibited zones of unit i.

Initial Status

At the beginning of the schedule, initial states of all the units and vehicles must be taken into account.

Must Run Units

These units include prescheduled units, which must be online, due to operating reliability and/or economic considerations.

Must out Units

Units which are on forced outages and maintenance are unavailable for commitment.

Network losses, transmission limit, voltage limit, *etc*. are considered in security constraint UC problem; however, they are not considered for UC for simplicity in this paper.

3. Data Structure and Algorithm of PSO for UC

PSO is similar to the other evolutionary algorithms in that the system is initialized with a population of random solutions. Each potential solution, call particles, flies in the D-dimensional problem space with a velocity which is dynamically adjusted according to the flying experiences of its own and its colleagues. The location of the jth particle is represented as $X_j = [x_{j1}, x_{j2}, \ldots, x_{jD}]^T$. The best previous position of the jth particle is recorded and called $pbest_j$. The index of the best *pbest* among all the particles is represented by the symbol g. The location $pbest_g$ is also called *gbest*. The rate of the velocity for the jth particle is represented as $V_j = [v_{j1}, v_{j2}, \ldots, v_{jD}]^T$. The modified velocity and position of each particle is calculated using the current velocity and the distance from *pbest*, *gbest* as (13) and (14).

$$v_{jit}(k+1) = \mathrm{w} * v_{jit}(k) + \mathrm{c}_1 * rand_1 * (pbest_{jit}(k) - x_{jit}(k)) + \mathrm{c}_2 * rand_2 * (\mathrm{g}best_{it}(k) - x_{jit}(k)), \tag{13}$$

$$x_{jit}(k+1) = x_{jit}(k) + v_{jit}(k+1). \tag{14}$$

In Eq. (13), the first term indicates the current velocity of the particle (inertia), second term presents the cognitive part of PSO, where the particle changes its velocity based on its own thinking and memory, and the third term is the social part of PSO, where the particle changes its velocity based on the social-psychological adaptation of knowledge. All the terms are multiplied by appropriate parameters. For UC problem, dimension D of a particle P is N times H. Dimensions of location and velocity are presented by 3 indices as x_{jit} and v_{jit}, respectively in this article for simplicity, where j=particle number, i= generating unit, t=time and k=step.

Binary PSO for Generating Units

To extend the real-valued PSO to binary space, Kennedy and Eberhart [19] calculate probability depending on the velocity to determine whether x_{jit} will be in on or off (0/1) state. They squashed v_{jit} using the following logistic function.

$$\Pr(v_{jit}) = \frac{1}{1+\exp(-v_{jit})} \tag{15}$$

$$I_{ji}(t) = \begin{cases} 1, & \text{if } U(0,1) < \Pr(v_{jit}) \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

where $U(0,1)$ is a uniform distribution between 0 and 1.

Therefore, the fitness (objective) function of UC is

$$TC_j = \sum_{i=1}^{N}\sum_{t=1}^{H}[(FC_i(P_i(t)) + SC_i(1-I_i(t-1)))I_c + W_i(\varphi_i EC_i(P_i(t)))I_e]I_{ji}(t) + Penalty \tag{17}$$

where power $P_i(t)$ of all the units i=1,2,…,N are calculated in ED for the schedule of particle j, $[I_{j1}(t), I_{j2}(t), \ldots, I_{jN}(t), N_{V2G}(t)]^T$. A large penalty is added if any constraint is violated. PSO is used to solve the problem in this paper. Binary PSO is used for generating units.

In this method, each PSO particle structure has the following fields for emission reduction in UC-V2G problem,

Particle P_i { Generating unit: An $N \times H$ binary matrix, X_i;

Fitness: A real-valued fitness TC; }.

Besides, some extra storage is needed for $pbest_i$, $gbest$ and temporary variables, which is acceptable and less than typical computer memory limit.

The steps for PSO algorithm for UC is given below:

1) *Initialize:* Initialize variables and parameters.

2) *Move:* Calculate velocity and location in all dimensions of the current swarm using (13)–(14). Use binary PSO (15)–(16) for generating units.

3) *Repair and calculate ED:* Repair each particle location if any constraint is violated there. It accelerates the process. Then, calculate ED of each feasible particle location (solution) using Lambda iteration.

4) *Evaluate fitness*: Evaluate each feasible location in the swarm using the emission objective function. Update *pbest* and *gbest* locations.

5) *Check and stop/continue:* Print the *gbest* and stop if the maximum number of generations is reached; otherwise increase iteration generation number and go back to Step 2.

4. Simulation Results

For UC, all calculations have been run on Intel(R) Core(TM)2 Duo 2.66 GHz CPU, 2.96 GB RAM, Microsoft Windows XP OS and Visual C++ compiler. Base 10-generator system is considered for simulation in the first stage for testing. Load demand, cost coefficients and emission coefficients including characteristics are shown in Tables 1, 2, and 3 respectively. The spinning reserve requirement is assumed to be 7% of the load demand of the Western Area of Saudi Arabia, cold start-up cost is double of hot start-up cost, and total scheduling period is 24 hours.

Average load demand of Western Area of Saudi Arabia is around 9,000 MW. In this stage, the investigator has no data for the thermal units of Western Area of Saudi Arabia. Thus standard 10-unit bench mark system is used to simulate the system for UC in the first stage to test the system. However, maximum load of 10-unit system is 1,500 MW. Therefore, the 10-unit system is copied six times to make a similar system of Western Area of Saudi Arabia for testing.

Table 1. Cost Coefficients and Unit Characteristics of 10-unit System.

Unit No.	P_i^{max} (MW)	P_i^{min} (MW)	a_i ($)	b_i ($/MW)	c_i ($/MW^2)	MU_i (h)	MD_i (h)	$h\text{-}cost_i$ ($)	$c\text{-}cost_i$ ($)	$c\text{-}s\text{-}hour_i$(h)	Ini. State (h)
U-1	455	150	1,000	16.19	0.00048	8	8	4,500	9,000	5	+8
U-2	455	150	970	17.26	0.00031	8	8	5,000	10,000	5	+8
U-3	130	20	700	16.60	0.002	5	5	550	1,100	4	-5
U-4	130	20	680	16.50	0.00211	5	5	560	1,120	4	-5
U-5	162	25	450	19.70	0.00398	6	6	900	1,800	4	-6
U-6	80	20	370	22.26	0.00712	3	3	170	340	2	-3
U-7	85	25	480	27.74	0.00079	3	3	260	520	2	-3
U-8	55	10	660	25.92	0.00413	1	1	30	60	0	-1
U-9	55	10	665	27.27	0.00222	1	1	30	60	0	-1
U-10	55	10	670	27.79	0.00173	1	1	30	60	0	-1

Table 2. Emission Coefficients of 10-unit System.

Unit	α_i (ton/h)	β_i (ton/MWh)	γ_i (ton/MW^{2}h)
U-1	10.33908	-0.24444	0.00312
U-2	10.33908	-0.24444	0.00312
U-3	30.03910	-0.40695	0.00509
U-4	30.03910	-0.40695	0.00509
U-5	32.00006	-0.38132	0.00344
U-6	32.00006	-0.38132	0.00344
U-7	33.00056	-0.39023	0.00465
U-8	33.00056	-0.39023	0.00465
U-9	35.00056	-0.39524	0.00465
U-10	36.00012	-0.39864	0.00470

Table 3. Forecasted Load Demand of western area on August 01, 2007.

Time (h)	Load (MW)	Time (h)	Load (MW)
1	8182.67	13	8624.62
2	8362.93	14	8757.82
3	8356.51	15	8779.08
4	8258.64	16	8698.66
5	8179.24	17	8437.02
6	7895.54	18	8238.61
7	7793.35	19	8073.28
8	8036.71	20	8398.55
9	8268.07	21	8237.82
10	8607.00	22	8256.29
11	8736.37	23	8229.21
12	8787.82	24	8189.44

According to the unit commitment and dispatch in Table 4, large units are base units for the base load. Large units are most of the time on and generating maximum power, except Units 6 and 7 during 24th hour. However, it is very difficult to investigate and explain the reason. Actually the system of the Western Area of Saudi Arabia is quite large. These results are promising and the investigators will work on it to modify the results and algorithm to fit the system.

5. Conclusions

The forecasting load is fed into UC problem and come up with schedule and dispatch of the thermal units. For unit commitment both cost and emission are considered. Actually cost and emission are trade-off. If cost increases, emission decreases, and vice-versa. In the next phase, UC will be tried to solve in multi-objective strategy to get a large Pareto front of cost and emission of the large system. Till now, real power is forecasted and used in the UC of the Western Area of Saudi Arabia.

Table 4. Dispatch for Western Area on August 01, 2007 using 60-unit system.

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23	H24
U 1-5	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455
U 6-7	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	0
U 8-12	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455	455
U 13-21	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
U 22	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
U 23	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
U 24	0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
U 25	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 26	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 27	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 28	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 29	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 30	162	162	162	156.4	145.7	109.2	92.2	128.6	156.3	162	162	162	162	162	162	162	162	156.4	132.2	162	153	156	153.2	162
U 31	56.4	30.1	29.1	20	20	20	20	20	20	71	80	80	74.5	80	80	72.8	39.2	20	20	35.3	20	20	20	80
U 32	0	30.1	29.1	20	20	20	20	20	20	71	80	80	74.5	80	80	72.8	39.2	20	20	35.3	20	20	20	80
U 33	56.4	30.1	29.1	20	20	20	20	20	20	71	80	80	74.5	80	80	72.8	39.2	0	0	0	20	20	20	80
U 34	0	30.1	29.1	20	20	20	20	20	20	0	0	0	0	0	80	72.8	39.2	20	20	35.3	20	20	20	80
U 35	56.4	30.1	29.1	20	20	20	20	20	20	71	80	80	74.5	80	80	72.8	39.2	20	20	35.3	20	20	20	80
U 36	56.4	30.1	29.1	20	20	20	20	20	20	71	80	80	74.5	80	80	72.8	39.2	20	20	35.3	20	20	20	80
U 37-40	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
U 41	25	25	25	25	0	0	0	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
U 42	0	25	25	25	25	0	0	0	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
U 43	10	10	10	10	10	0	0	0	10	10	20.7	27.6	10	22.6	10	10	10	10	0	10	10	0	10	55
U 44	10	10	10	10	10	0	0	0	10	10	20.7	27.6	0	22.6	10	10	0	10	0	10	10	10	10	55
U 45	10	10	10	0	10	0	0	0	10	10	20.7	27.6	10	22.6	10	10	10	0	10	0	10	10	0	55
U 46	10	10	10	0	0	0	0	0	0	10	20.7	27.6	10	22.6	10	10	0	0	0	10	0	0	0	55

Table 4. Contd.

U 47	10	0	0	0	0	0	0	0	0	10	20.7	27.6	10	22.6	10	10	0	0	0	10	0	0	0	55
U 48	10	0	0	0	0	0	0	0	0	10	20.7	27.6	10	22.6	10	10	0	0	0	10	0	10	0	55
U 49	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	0	0	0	0	0	0	14.6
U 50	10	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	0	10	0	0	0	14.6
U 51	10	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	0	0	0	0	0	0	14.6
U 52	10	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	0	0	0	0	0	0	0	14.6
U 53	10	0	0	0	10	0	0	0	0	0	10	10	0	10	10	10	0	0	0	0	0	0	0	14.6
U 54	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10	0	0	0	0	0	0	0	0	14.6
U 55	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	0	0	0	0	0	0	0	0	10
U 56	0	0	0	0	0	0	0	0	10	10	0	0	0	0	0	0	10	0	0	10	0	0	0	10
U 57	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	10
U 58	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	10	0	0	0	0	0	0	0	10
U 59	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
U 60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
Emission (ton)	938.4	1795.4	80794.4	80150.2	80307.8	77717.2	77139.5	79574.9	81978.3	84119.1	83867.8	83491.2	3282.8	83835.	3582.6	4148.8	1394.4	1776.2	9076.8	1709.0	1234.8	2138.0	9947.3	8356.99
Max. cap (MW)	9027	9202	9202	9147	9117	8812	8812	8897	9202	9507	9617	9672	9507	9672	9697	9642	9312	9067	8957	9342	9147	9147	9092	9062
Demand (MW)	8182.7	8362.9	8356.5	8258.6	8179.2	7895.5	7793.4	8036.7	8268.1	8607	8736.4	8787.8	8624.6	8757.8	8779.1	8698.7	8437	8238.6	8073.3	8398.5	8237.8	8256.3	8229.2	8189.4
Reserve (MW)	844.3	839.1	845.5	888.4	937.8	916.5	1018.6	860.3	933.9	900	880.6	884.2	882.4	914.2	917.9	943.3	875	828.4	883.7	943.5	909.2	890.7	862.8	872.6
Total fuel cost: 4332905.31$																								
Total emission = 1934791.47 ton																								

Note: "U *x*" stands for unit number *x*, "U *x-y*" stand for unit number *x* to *y* if all the units generate same UC schedule and dispatch; *H* stands for hour. Dispatches of all the units are in MW, "Max. cap" stands for maximum capacity. Dispatches of all the units are in MW.

References

[1] **Happ, H.H., Johnson, R.C.** and **Wright, W.J.,** "Large scale hydrothermal unit commitment-method and results," *IEEE Trans. Power Appa. Syst.*, **PAS-90**(3): 1373-1384, May/Jun (1971).

[2] **Baldwin, C.J., Dale, K.M.** and **Dittrich, R.F.,** "A study of economic shutdown of generating units in daily dispatch," *IEEE Trans. Power Appa. Syst.*, **PAS-78**: 1272-1284, (1960).

[3] **Senjyu, T., Shimabukuro K., Uezato, K.** and **Funabashi, T.,** "A fast technique for unit commitment problem by extended priority list," *IEEE Trans. Power Syst.*, **18**(2): 882-888, May (2003).

[4] **Cohen, A.I.** and **Yoshimura, M.,** "A branch-and-bound algorithm for unit commitment," *IEEE Trans. Power Appa. Syst.*, **PAS-102**: 444-451, Feb. (1983).

[5] **Ouyang, Z.** and **Shahidehpour, S.M.,** "An intelligent dynamic programming for unit commitment application," *IEEE Trans. Power Syst.*, **6**(3): 1203-1209, Aug. (1991).

[6] **Chen, C.S., Chuang, H.J.** and **Fan, L.I.,** "Unit commitment of main transformers for electrified mass rapid transit systems," *IEEE Trans. Power Delivery*, **17**: 747-753, Jul. (2002).

[7] **Pang, C.K., Sheble, G.B.** and **Albuyeh, F.,** "Evaluation of dynamic programming based methods and multiple area representation for thermal unit commitments," *IEEE Trans. Power Appa. Syst.*, **PAS-100**: 1212-1218, Mar. (1981).

[8] **Svoboda, A.J., Tseng, C.L., Li, C.A.** and **Johnson, R.B.**, "Short-term resource scheduling with ramp constraints [power generation scheduling]," *IEEE Trans. Power Syst.*, **12**(1): 77-83, Feb. (1997).

[9] **Lee, F.N.,** "A fuel-constrained unit commitment method," *IEEE Trans. Power Syst.*, **4**(3): 1208-1218, Aug. (1989).

[10] **Virmani, S., Adrian, E.C., Imhof, K.** and **Mukherjee, S.,** "Implementation of a Lagrangian relaxation based unit commitment problem," *IEEE Trans. Power Syst.*, **4**(4): 1373-1380, Nov. (1989).

[11] **Shaw, J.J.,** "A direct method for security-constrained unit commitment," *IEEE Trans. Power Syst.*, **10** (3): 1329-1342, Aug. (1995).

[12] **Peterson, W.L.** and **Brammer, S.R.,** "A capacity based Lagrangian relaxation unit commitment with ramp rate constraints," *IEEE Trans. Power Syst.*, **10**(2): 1077-1084, May (1995).

[13] **Damousis, I.G., Bakirtzis, A.G.** and **Dokopoulos, P.S.,** "A solution to the unit-commitment problem using integer-coded genetic algorithm," *IEEE Trans. Power Syst.*, **19** (2): 1165-1172, May (2004).

[14] **Senjyu, T., Saber, A.Y., Miyagi, T., Shimabukuro, K., Urasaki, N.** and **Funabashi, T.,** "Fast technique for unit commitment by genetic algorithm based on unit clustering," *IEE Proc., Gen. Transm. Dist.*, **152**(5): 705-713, Sep. (2005).

[15] **Cheng, C.P., Liu, C.W.** and **Liu, C.C.,** "Unit commitment by Lagrangian relaxation and genetic algorithms," *IEEE Trans. Power Syst.*, **15**(2): 707-714, May (2000).

[16] **Kazarlis, S.A., Bakirtzis, A.G.** and **Petridis, V.,** "A genetic algorithm solution to the unit commitment problem," *IEEE Trans. Power Syst.*, **11**(1): 83-92, Feb. (1996).

[17] **Mori, H.** and **Matsuzaki, O.,** "Application of priority-list-embedded tabu search to unit commitment in power systems," *Inst. Elect. Eng. Japan*, **121-B**(4): 535-541 (2001).

[18] **Juste, K.A., Kita, H., Tanaka, E.** and **Hasegawa, J.**, "An evolutionary programming solution to the unit commitment problem," *IEEE Trans. Power Syst.*, **14**(4): 1452-1459, Nov. (1999).

[19] **Kennedy, J.** and **Eberhart, R.C.,** "Particle swarm optimization," *Proc. IEEE Int. Conf. on Neural Networks*, pp: 1942-1948, Perth, Australia (1995).

[20] **Shi, Y.** and **Eberhart, R.C.**, "Parameter selection in particle swarm optimization," *Proc. of the Seventh Annual Conference on Evolutionary Programming*, IEEE Press (1998).

[21] **Kennedy, J.** and **Eberhart, R.C.,** "A discrete binary version of the particle swarm algorithm," *Proc. of IEEE Conf. on Systems, Man, and Cybernetics*, pp: 4104-4109 (1997).

[22] **Ting, T.O., Rao, M.V.C.** and **Loo, C.K.,** "A novel approach for unit commitment problem via an effective hybrid particle swarm optimization," *IEEE Trans. Power Syst.*, **21**(1): 411-418, Feb. (2006).

[23] **Gaing, Z.L.,** "Particle swarm optimization to solving the economic dispatch considering the generator constraints," *IEEE Trans. Power Syst.*, **18**(3): 1187-1195, Aug. (2003).

[24] **Jeyakumar, D.N., Jayabarathi, T.** and **Raghunathan, T.,** "Particle swarm optimization for various types of economic dispatch problems," *Electrical Power and Energy Systems*, **28**: 36-42 (2006).

[25] **Yoshida, H., Kawata, K., Fukuyama, Y., Takayama, S.** and **Nakanishi, Y.,** "A particle swarm optimization for reactive power and voltage control considering voltage security assessment," *IEEE Trans. Power Syst.*, **15** (4): 1232-1239, Nov. (2000).

[26] **Miranda, V.,** "Evolutionary algorithms with particle swarm movements," *IEEE 13th Int. Conf. on Intelligent Syst. Appli. to Power Syst. (ISAP)*, pp: 6-21, VA, USA, Nov. 6-10, (2005).

[27] **Dorigo, M., Maniezzo, V.** and **Colorni, A.,** "The ant system: optimization by a colony of cooperating agents," *IEEE Trans. Syst. Man Cybernetics*, **26**(2): 29-41, Part B (1996).

[28] **Dorigo, M.** and **Gambardella, L.M.,** "Ant colony system: a cooperative learning approach to the traveling salesman," *IEEE Trans Evolutionary Computation,* **1**(1): 53-65 (1997).

[29] **Huang, S.J.,** "Enhancement of hydroelectric generation scheduling using ant colony system based optimization approaches," *IEEE Trans Energy Conversion*, **16**(3): 296-301, (2001).

[30] **Shi, L., Hao, J., Zhou, J.** and **Xu, G.,** "Ant colony optimisation algorithm with random perturbation behaviour to the problem of optimal unit commitment with probabilistic spinning reserve determination," *Electric Power System Research*, **69**: 295-303(2004).

[31] **Simon, S.P., Padhy, N.P.** and **Anand, R.S.,** "An ant colony system approach for unit commitment problem," *Electrical Power and Energy Systems*, **28**(5): 315-323, Jun. (2006).

[32] **Satoh, T.** and **Nara, K.,** "Maintenance scheduling by using simulated annealing method [for power plants]," *IEEE Trans. Power Systems.*, **6**(2): 850-857, May (1991).

[33] **Wong, S.Y.W.,** "An enhanced simulated annealing approach to unit commitment", *Electric Power Energy Systems.*, **20**: 359-368, May (1998).

[34] **Zhuang, F.** and **Galiana, F.D.,** "Unit commitment by simulated annealing," *IEEE Trans. Power Syst.*, **5**(1): 311-318, Feb. (1990).

[35] **Mantawy, A.H., Abel-Mogid, Y.L.** and **Selim, S.Z.,** "A simulated annealing algorithm for unit commitment," *IEEE Trans. Power Systems.*, **13**(1): 197-204, Feb. (1998).

[36] **Mantawy, A.H., Abel-Mogid, Y.L.** and **Selim, S.Z.,** "Integrating genetic algorithms, tabu search, and simulated annealing for the unit commitment problem," *IEEE Trans. Power Systems*, **14**(3): 829-836, Aug. (1999).

[37] **Cheng, C.P., Liu, C.W.** and **Liu, C.C.,** "Unit commitment by annealing-genetic algorithms," *Electrical Power and Energy Systems*, **24**: 149-158 (2002).

[38] **Purushothama, G.K.** and **Jenkins, L.,** "Simulated annealing with local search - A hybrid algorithm for unit commitment," *IEEE Trans. Power Systems*, **18**(1): 273-278, Feb. (2003).

[39] **Mantawy, A.H.,** "A genetic algorithm solution to a new fuzzy unit commitment model," *Electric Power Systems Research*, **72**: 171-178 (2004).

[40] **El-Saadawi, M.M., Tantawi, M.A.** and **Tawfik, E.,** "A fuzzy optimization based approach to large scale thermal unit commitment," *Electric Power Systems Research*, **72**: 245-252 (2004).

[41] **Padhy, N.P.,** "Unit commitment using hybrid models: a comparative study for dynamic programming, expert system, fuzzy system and genetic algorithms," *Electrical Power and Energy Systems*, **23**: 827-836 (2000).

[42] **Su, C.C.** and **Hsu, Y.Y.,** "Fuzzy dynamic programming: An application to unit commitment," *IEEE Trans. Power Systems*, **6**(3): 1231-1237, Aug. (1991).

[43] **Saneifard, S., Prasad, N.R.** and **Smolleck, H.A.,** "A fuzzy logic approach to unit commitment," *IEEE Trans. Power Systems*, **12**(2): 988-995, May (1997).

[44] **Saber, A.Y., Senjyu, T., Miyagi, T., Urasaki, N.** and **Funabashi, T.,** "Fuzzy unit commitment scheduling using absolutely stochastic simulated annealing," *IEEE Trans. Power Systems*, **21**(2): 955-964, May (2006).

[45] **Kempton, W., Tomic, J., Letendre, S., Brooks, A.** and **Lipman, T.,** "*Vehicleto-Grid Power: Battery, Hybrid and Fuel Cell Vehicles as Resources for Distributed electric Power in California, Davis, CA*," Institute of Transportation Studies, Report # IUCD-ITS-RR 01-03, (2005).

[46] **Tomic, J.** and **Kempton, W.,** " Using fleets of electric-drive vehicles for grid support," *Journal of Power Sources*, **168**(2): 459-468, 1 Jun. (2007).

[47] **Kempton, W.** and **Tomic, J.,** "Vehicle to grid fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, **144**(1): 268-279, 1 Jun. (2005).

[48] **Kempton, W.** and **Tomic, J.,** "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, **144**(1): 280-294, 1 Jun. (2005).

[49] **Williams, B.D.** and **Kurani, K.S.,** "Estimating the early household market for light-duty hydrogen-fuel-cell vehicles and other "Mobile Energy" innovations in California: A constraints analysis," *Journal of Power Sources*, **160**(1): 446-453, 29 Sep. (2006).

[50] **Williams, B.D.** and **Kurani, K.S.,** "Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: "Mobile Electricity" technologies and opportunities," *Journal of Power Sources*, **166**(2): 549-566, 15 Apr. (2007).

[51] **Kempton, W.** and **Kubo, T.,** "Electric-drive vehicles for peak power in Japan," *Energy Policy*, **28**(1): 9-18 (2000).

[52] **Saber, A.Y.** and **Venayagamoorthy, G.K.,** "Unit commitment with vehicle-to-grid using particle swarm optimization," *IEEE Power Tech 2009, 28 June–2 July 2009, Bucharest, Romania*, pp: 1-8 (2009).

[53] **Saber, A. Y.** and **Venayagamoorthy, G. K.**, "Intelligent unit commitment with vehicle-to-grid – A cost-emission optimization," *Journal of Power Sources*, **195**(3): 898-911, Feb. (2010).

[54] **Saber, A.Y.** and **Venayagamoorthy, G.K.,** "One million plug-in electric vehicles on the road by 2015," *IEEE Conference on Intelligent Transportation Systems, ITSC09*, *October 3-7, 2009, St. Louis, Missouri, USA*, pp: 141-147 (2009).

[55] **Saber, A.Y.** and **Al-Shareef, A.,** "Load forecasting of a desert: A computational intelligence approach," *International Conference on Systems Application to Power Systems, ISAP 2009, November 8-12, 2009, Curitiba, Brazil* (2009).

[56] **Saber, A.Y.** and **Venayagamoorthy, G.K.,** "V2G scheduling – A modern approach to unit commitment with vehicle-to-grid using particle swarm optimization," *IFAC Symposium on Power Plants and Power Systems*, *July 5-8, 2009, Tampere Hall, Finland* (2009).

[57] **Kennedy, J.** and **Eberhart, R.C.,** "Particle swarm optimization," *Proc. IEEE Int. Conf. on Neural Networks*, *Perth, Australia*, pp: 1942-1948 (1995).

[58] **Kennedy, J.** and **Eberhart, R. C.,** "A discrete binary version of the particle swarm algorithm," *Proc. of IEEE Conf. on Systems, Man, and Cybernetics*, pp: 4104-4109 (1997).

تطبيقات حشد الجزئيات لحل مشكلة ارتباط وحدات التوليد بالمنطقة الغربية من المملكة العربية السعودية

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المستخلص. ارتباط الوحدات في نظم القوى يحتاج إلى جدولة الطاقة من كل المصادر، إلا أن ذلك يخضع لعدد من المحددات. ارتباط الوحدات يحتاج في البداية إلى دراسة التنبؤ بالأحمال بالإضافة إلى الطاقة الاحتياطية لكل فترة من الفترات، وذلك لتخفيض التكلفة.

في هذه الورقة تم تطبيق نظام حشد الجزيئات طبقًا لتخفيض: أولاً التكلفة، وثانيًا الانبعاث، وثالثًا التكلفة والانبعاث معًا.

تخفيض التكلفة وتخفيض الانبعاث يعملان متعاكسان متضادان، إذا قلت التكلفة زاد الانبعاث وإذا انخفض الانبعاث زادت التكلفة والعكس صحيح.

تمت دراسة التنبؤ بالأحمال في المنطقة الغربية سابقًا، واستخدمت حاليًا لحل مشكلة ارتباط الوحدات. في هذه الدراسة، قدرت تكلفة التوليد لأربع وعشرين ساعة بـ (٤٣٣٢٩٠) دولارًا والانبعاث بـ (١٩٣٤٧٩) طنًا.