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جدولة وحدات توليد الطاقة الكهربائية مقيدة الإنبعاثات في دولة الكويت عن طريق الخوارزميات الجينية

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خلاصة

مشكلة جدولة وحدات توليد الطاقة الكهربائية المقيدة الإنبعاثات هي إمتداد لمشكلة جدولة وحدات توليد الطاقة الكهربائية التقليدية التي تأخذ بعين الإعتبار التقليل من كمية الغازات الدفيئة المنبعثة من وحدات التوليد في المحطات الكهربائية. وتعرض هذه الورقة حل لمشكلة جدولة وحدات توليد الطاقة الكهربائية في محطات الطاقة الحرارية في الكويت مع تقليل الإنبعاثات، عن طريق إستخدام الخوارزميات الجينية . وتتميز الخوارزمية الجينية بكفاءة تقنية التحسين الأمثل إستناداً إلى مبدأ التطور البيولوجي . ويتم حل هذه المشكلة المعقدة والغير خطية على مرحلتين: تستخدم في المرحلة الأولى الخوارزمية الجينية لأداء التوزيع الإقتصادي للحمل على وحدات التوليد المتصلة بالشبكة مع الأخذ بعين الإعتبار جميع قيود نظام توليد الطاقة الكهربائية ، بينما تستخدم في المرحلة الثانية الخوارزمية الجينية أيضاً للبت في حالات وحدات توليد الطاقة الكهربائية (تشغيل/إطفاء) . وأظهرت نتائج محاكاة النظام كفاءة الخوارزمية الجينية للحصول على الحل الأمثل النهائي لمشكلة تقييد الإنبعاثات من المحطات الكهربائية في نظام توليد الطاقة في دولة الكويت .

Emission constrained unit commitment of Kuwait power generation system using genetic algorithm

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ABSTRACT

Emission Constrained Unit Commitment (ECUC) is an extension of the conventional Unit Commitment (UC) problem that takes into consideration the minimization of the amount of greenhouse gases emitted from generating units in power plants. This paper presents a Genetic Algorithm (GA) solution of ECUC for thermal power plants in Kuwait. GA is an efficient optimization technique based on the principle of biological evolution. This complicated nonlinear ECUC problem is solved in two stages; the first stage uses GA to perform the Economic Dispatch (ED) taken into account all system constraints, while the second stage uses also GA to decide the ON/OFF status of the generating units. The simulation results indicated the efficient convergent of the GA to the final optimal solution of the ECUC in Kuwait generation system.

Keywords: Economic dispatch; genetic algorithm; greenhouse gases; optimization techniques; unit commitment.

NOMENCLATURE

N	Number of generating units.
T	Number of time intervals in hours.
TC	Total cost.
FC	Fuel cost.
EC	Emission level.
SUC_i^t	Startup cost for unit i at hour t.
SDC_i^t	Shutdown cost for unit i at hour t.
D^t	Total load demand at hour t.
R^t	System reserve at hour t.
$u_i(t)$	Operation status of unit i at hour t (ON/OFF).
P_i^t	Output power of ith unit at hour t.

$P_{i,min}$	Minimum generated power of *i*th unit.
$P_{i,max}$	Maximum generated power of *i*th unit.
T_i^c	Duration of operating cycle *c* for unit *i*.
MUT_i	Minimum up time limit of unit *i*.
MDT_i	Minimum down time limit of unit *i*.

INTRODUCTION

The Economic Dispatch (ED) problem in power systems determines the optimal megawatt outputs of generating units that minimize the total operating cost for a given load demand. But Unit Commitment (UC) problem in power systems is an optimization problem that is designed to determine the optimum combination from the available generating units to supply a given load at minimum operational cost subject to many system and operational constraints (Wood & Wollenberg 1996).

The literature of UC problem and its solution methods are surveyed in Padhy (2004). Several methods have been developed to solve UC problem, such as Priority Listing (PL) (Burns & Gibson 1975; Lee & Feng 1992), Dynamic Programing (DP) (Snyder *et al*., 1987; Lower 1966), Lagrangian Relaxation (LR) (Virmani *et al*., 1989; Zhuang & Galiana 1988), Interior Point (IP) methods (Madrigal & Quintana 2000; Farhat & El-Hawary 2009), Tabu Search (TS) (Mori & Matsuzaki 2000; Rajan *et al*., 2002), Artificial Neural Networks (ANN) (Sasaki *et al*., 1992; Liang & Kang 2000), Particle Swarm Optimization (PSO) (Kennedy & Eberhart 1995; Ting *et al*., 2006), and Genetic Algorithms (GA) (Swarup & Yamashiro 2002; Ma *et al*., 1995; Orero & Irving 1996; Maifeld & Sheble 1996; Sood *et al*., 2003).

Since the implementation of US clean air act amendments of 1990 and similar acts by European and Japanese governments, environmental constraints have become most important for power utilities (Group 1995). The single objective cost function of classical UC could no longer be considered alone, due to environmental concerns arising from the emissions produced by electric power plants. The generation of electricity from fossil fuel releases several greenhouse gases, such as Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x) and Sulfur Oxides (SO_x), into the atmosphere. Hence, the purpose of Emission Constrained Unit Commitment (ECUC) problem is to determine the optimal amount of generated power from the generating units by minimizing simultaneously the fuel cost and emission level subject to various system constraints. As a result, ECUC problem solution will assign less power to those generators with high fuel cost and high emission level, and thus emission is reduced.

Many researchers have considered greenhouse gases emission either in the objective function or treated emissions as additional constraints (Kulkarni *et al.*, 2000). The difficulty of the ECUC problem arises from the non-linearity nature of the objective function and constraints. Many classical techniques are inefficient and very comprehensive regarding computer requirements when solving ECUC problem. Recently, extensive research has been carried out to implement Artificial Intelligence (AI) based technique for solving the nonlinear problem of ECUC. GA has a highly simplified model and posses an efficient characteristic for solving ECUC problem in the presence of non-linearity and inequality constraints.

In this paper, an improved GA is developed and tested to solve the ECUC problem. The equality constraints of power balance and inequality constraints of generation limits are taken into consideration. The proposed approach is applied on Kuwait generation system.

ECUC PROBLEM FORMULATION

Unit Commitment (UC) Cost

The objective of the UC optimization problem is to minimize the total generation cost over a scheduling period subject to units and load constraints. UC problem can be expressed as number of sub-problems of ED solutions equal to the number of intervals of study periods taking into consideration all unit and load constraints. The total operating cost of the UC problem is expressed as the sum of fuel cost, startup costs, and shutdown costs of the generating units (Wood & Wollenberg 1996).

$$TC = FC + SUC + SDC \tag{1}$$

The fuel cost function:

$$FC = \sum_{t=1}^{T} \sum_{i=1}^{N} \left(FC_i \left(P_i^t \right) \cdot u_i \left(t \right) \right) \tag{2}$$

The input of thermal power plant is generally measured in MBtu/h and the output power is measured in MW. This input-output relation is converted to a fuel cost curve representing the relationship of the operating cost of a fossil-fired thermal unit. To simplify the fuel-cost function, these curves can be expressed in form of quadratic functions of the real power generation. The fitted curves are monotonously increasing and convex. Then, a quadratic polynomial with coefficients a_i, b_i, and c_i is used to express the fuel cost as a function of the generating power P_i^t in the ith unit

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

The startup cost is considered only for units which change their state from OFF to ON. The hot start up and cold startup are identified according to number of OFF hours before ON. This can be expressed as:

$$SUC = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(SUC_i(t)\cdot u_i(t)\right) \tag{4}$$

The shutdown cost is also considered for units which change their state from ON to OFF. This can be expressed as:

$$SDC = \sum_{t=1}^{T}\sum_{i=1}^{N}\left(SDC_i(t)\cdot u_i(t)\right) \tag{5}$$

There are two types of constraints that must be considered in any UC problem. One is associated with system loads, while the other is associated with the generating units.

1. *Load Constraints:*

- Power balance of load and generation: Total load demand is equal to the sum of generator output, and it can be expressed as

$$D^t = \sum_{i=1}^{N}\left(P_i^t\cdot u_i(t)\right) \qquad t = 1,\cdots,T \tag{6}$$

- Spinning reserve of the power system: Spinning reserve can be defined as the total amount of maximum power available from all committed units minus the present total load demand. Also, the total available power during an interval of study must be greater than or equal to the summation of total load demand plus reserve at such interval. Generally, the amount of power reserve should be greater than the installed power capacity of the largest generating unit. This can be expressed as the following:

$$\sum_{i=1}^{N}\left(P_{i,max}\cdot u_i(t)\right) \ge \left(D^t + R^t\right) \qquad t = 1,\cdots,T \tag{7}$$

2. *Unit Constraints:* Unit constraints are considered because scheduled power for a certain unit must be within the minimum and maximum limits of such unit. Lower and upper limits of ith unit generated power can be expressed as:

$$P_{i,min} \le P_i \le P_{i,max} \tag{8}$$

The minimum up time constraint indicate that a generator unit must be ON for a minimum time before it can be shutdown. On the other hand, the minimum down time constraint indicate that a generating unit must be OFF for a minimum time before it can be restarted. Minimum up and down times of ith unit can be represented as:

$$\begin{cases} T_i^c \geq MUT_i \\ -T_i^c \geq MDT_i \end{cases} \tag{9}$$

Greenhouse Gas Emission

The solution to the UC problem will give the amount of real power to be generated by different units at a minimum fuel cost for particular demand while taking into account load and unit constraints. But the amount of greenhouse gases emission is not considered in classical UC. CO_2 emission factors are estimated using fuel carbon intensity of the consumed fuel. Similarly SO_x emission factors are estimated by the fuel sulfur content. For combined-cycle plants, NO_x emission factors are developed on the basis of the prime mover technology and size. The amount of emission from a fossil based thermal generating unit depends on the amount of power generated by the unit. The following expression is used to model greenhouse gases emission from different power plants:

$$EC_i\left(P_i^t\right) = \gamma_i + \beta_i \cdot \left(P_i^t\right) + \alpha_i \cdot \left(P_i^t\right)^2 \tag{10}$$

where γ_i, β_i, and α_i are emission coefficients of ith unit, which are obtained by curve fitting of recorded data of emitted gases in different power plants (Cai *et al.*, 2012).

Emission Constrained Unit Commitment (ECUC)

The economic dispatch and emission dispatch are two different optimization problems using Equation (3) and Equation (10). In this paper, the two objectives are converted into a single objective function by introducing a price penalty factor h_i to combine fuel cost plus the implied emission cost (Kulkarni *et al.*, 2000). Then, the multi-objective problem of ECUC can be formulated as:

$$F\left(P_i^t\right) = w_1 \cdot \sum_{i=1}^{N} FC_i\left(P_i^t\right) + w_2 \cdot \sum_{i=1}^{N} h_i \cdot EC_i\left(P_i^t\right) \tag{11}$$

where w_1 and w_2 are weight factors.

Various methods have been suggested to calculate price penalty factor h_i and among that the maximum price penalty factor has been chosen, as it offers a very good solution for emission restricted less cost condition (Kulkarni *et al.*, 2000). The maximum price penalty factor h_i of each generator is the ratio between the fuel cost and emission at its maximum power output and it is represented as the following:

$$h_i = \frac{FC_i\left(P_{i,max}\right)}{EC_i\left(P_{i,max}\right)} \tag{12}$$

where $FC_i\left(P_{i,max}\right)$ is the highest fuel-cost unit and $EC_i\left(P_{i,max}\right)$ is the highest pollutant emission unit.

Similarly, the price penalty factors for SO_x and NO_x are calculated. The product of the calculated emission value and price penalty factor decides the cost function of emission. The price penalty factor h_i unifies the emission with the normal fuel costs and the total operating cost of the system (*i.e.*, the cost of fuel + the implied cost of emission). Once the value of price penalty factor is determined, the problem reduces to a simple economic dispatch problem.

The two weighting factors added in Equation (11) can be used for three types of economic dispatch problems. The case when $w_1 = 1$ and $w_2 = 0$ is to yield the classical economic dispatch problem while the pure emission dispatch is the case when $w_1 = 0$ and $w_2 = 1$. To establish the combined economic and emission dispatch problem, both weighting factors must equal 1, for example $w_1 = 1$ and $w_2 = 1$ (Mandal & Chakraborty, 2008).

THE PROPOSED ALGORITHM

The proposed algorithm consists mainly of two stages to solve ECUC optimization problem. In the first stage, the constrained nonlinear optimization of GA MATLAB toolbox is applied to solve the ED problem (MATLAB, 2011). ED is separately applied to each interval of UC study period. A GA for solving ECUC is applied in the second stage. For each individual in each generation, a weighting factor is given according to its violation to the constraints. Good individuals have less weighting factors than bad ones. The proposed algorithm will be briefly explained next.

ED and Individual Generation

In large scale power systems, UC problem becomes very complicated due to the large number of variables. The search space will be large and getting the optimal solution will be very difficult. Therefore, the ECUC problem is decomposed into two stages. ED is separately applied on each interval of UC study, in order to obtain the best schedule of operating units at all intervals. The results obtained from all ED solution intervals are grouped and saved as one individual solution as shown in the encoding scheme of Figure 1. In this figure, each column expresses generation schedule of one interval, while the state of each unit is expressed in the row. The encoding must be carefully designed to utilize the ability of GA to efficiently achieve the objective function by testing the fitness function. For Kuwait generation system which consists of $N = 83$ units and $T = 24$ intervals, the solution is saved as one row with $(N.T)$ bits. For example, the first bit is the state of unit one at interval one $(u_1 t_1)$, and the second bit is the state of unit one at interval two $(u_1 t_2)$. The GA execution process consists of several steps to adopt the algorithm parameters namely population size, intermediate recombination, real value cross over and mutation as well as elitism reinsertion. This process is repeated until the states of all units for all intervals are saved.

$$\begin{bmatrix} u_1t_1 & u_1t_2 & \cdots & u_1t_T \\ u_2t_1 & u_2t_2 & \cdots & u_2t_T \\ \vdots & \vdots & \ddots & \vdots \\ u_Nt_1 & u_Nt_2 & \cdots & u_Nt_T \end{bmatrix}$$

Fig. 1. The proposed two dimensional encoding scheme

Also, the saved individual may have the minimum generation cost but it may not satisfy all constraints such as minimum up time and minimum down time. For this reason, minimum up and minimum down times are checked for each unit and the number of changes needed to satisfy these time constraints is identified. The pre-saved individual is modified by randomly changing unit states according to the number of identified changes to satisfy minimum up and minimum down times.

GA for ECUC

In the second stage, a GA is applied to obtain the optimal solution of ECUC problem, as summarized in the flow chart of Figure 2. In GA population generations, each individual contains a complete schedule of all generating units for all intervals. An initial generation cost is assumed to be equal to the summation of generation costs obtained from all ED solutions executed in stage one. In each GA, individuals are tested for all load and unit constraints. These individuals are weighted according to their constraints satisfaction. Bad individuals are weighted with a very high weighting factor, so they would have less chance competing in the next generation. The weighting factor for each individual is increased by one with each violation in load or unit constraints. Cost of any violated individual is obtained by multiplying the weighting factor of such individual by the initial generation cost obtained for pre-saved individual in stage one. ED is run only for individuals who satisfy all load and unit constraints.

RESULTS AND APPLICATION ON KUWAIT GENERATION SYSTEM

Electrical energy in Kuwait is rapidly increasing with a peak load rate of increase by 6–8% per year. Therefore, the country plans to install new power plants to cover the increasing demand. Development of Kuwait power stations' installed capacity is shown in Figure 3.

There are 6 power stations in Kuwait composing a total of 83 generators. These power stations are owned by Ministry of Electricity and Water MEW. These power stations are (1) Shuwaikh, (2) Shuaiba South, (3) Doha East, (4) Doha West, (5) Az-Zour South, and (6) Sabiya. Detailed information of these power stations such as number of generators and their installed capacity are described in Table 1 (Center, 2011).

The maximum system load in 2010 was registered on June 15th as 10,890 MW.

Hourly load curve for day of peak load is shown in Figure 4.

The proposed GA has been applied on the 83 unit generation system in Kuwait in order to validate its ability of solving ECUC optimization problem and identify the optimal unit combination. The period of study for the optimization problem is assumed to be 24 hours. The load is assumed to be fixed for each hour of study. The following optimization parameters are used in the simulation: hot start cost for steam turbines = \$4000, cold start cost for steam turbines = \$8000, hot start cost for gas turbines = \$50, cold start cost for gas turbines = \$100, minimum up/down time of 300 MW steam turbine = 5 hours, minimum up/down time of 150 MW steam turbine = 4 hours, minimum up/down time for gas turbines = 1 hour, hot start time of 300 MW steam turbine = 5 hours, hot start time of 150 MW steam turbine = 4 hours, hot start time for gas turbine = 0 hour, population size = 83, generations = 200, and number of maximum iteration = 200. Many test cases are applied under different percentage reserve constraints with and without greenhouse gases emission penalties. The generation cost functions and emission functions of the different generating units are listed in Appendix A.

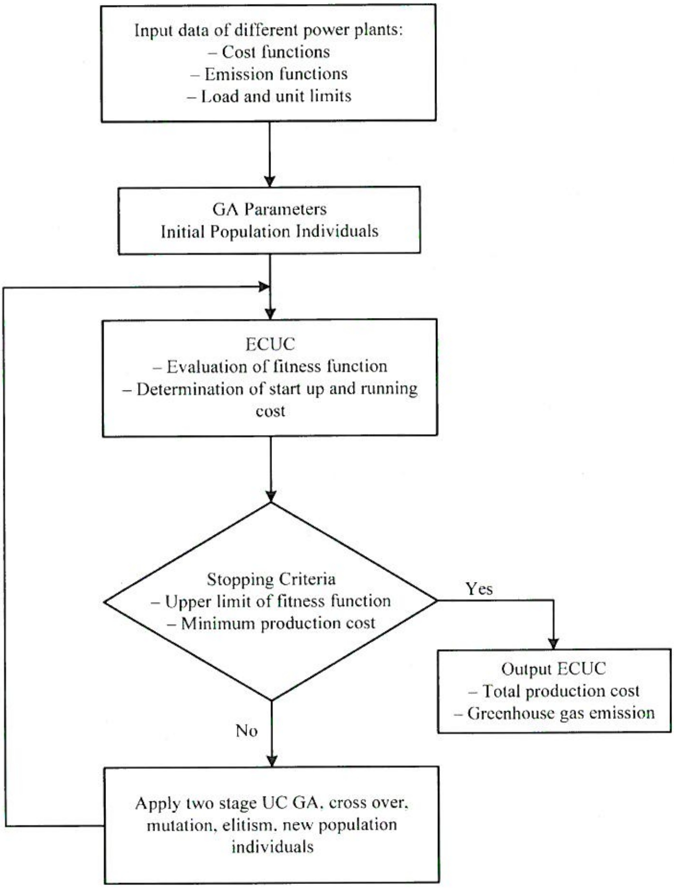

Fig. 2. Flow chart of ECUC

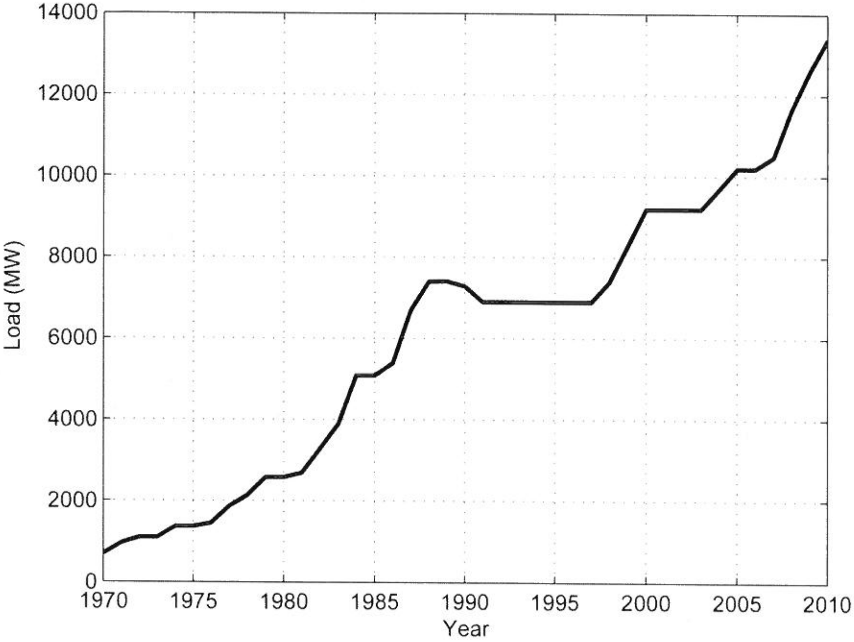

Fig. 3. Development of Kuwait power stations' installed capacity (Center, 2011)

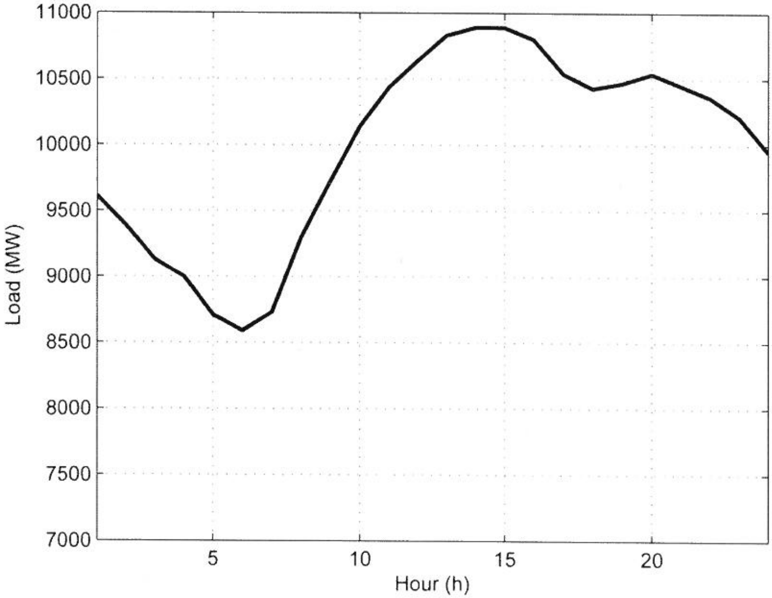

Fig. 4. Load curve for day of peak load (June 15th 2010)

Table 1. Power stations in Kuwait

	Steam Turbines			Gas Turbines			
Power Station	**No.**	**Installed Capacity**	**Total Installed Capacity**	**No.**	**Installed Capacity**	**Total Installed Capacity**	**Total**
		MW	MW		MW	MW	MW
(1)	–	–	–	6	42	252	252
(2)	6	134	804	–	–	–	804
(3)	7	150	1050	6	18	108	1158
(4)	8	300	2400	5	28.2	141	2541
	8	300	2400	4	27.75	111	
(5)	2	280	560	8	130	1040	4936
	–	–	–	5	165	825	
(6)	8	300	2400	6	41.7	250.2	2900.2
	–	–	–	4	62.5	250	
Total:	**39**	–	**9614**	**44**	–	**2977.2**	**12591.2**

Three different cases with zero, 5%, and 8% of spinning reserve are executed using the improved GA. The available power reserves at all intervals are displayed in Table 2 for test cases with and without emission penalties. The change of the objective function with each population generation of GA is shown in Figure 5. The startup cost and the running cost are listed in Table 3 for the test cases with and without emission penalties. The results of the startup cost and running cost are compared. From this comparison, the startup cost and the running cost are increased with the increase of spinning reserve. Similarly, the start up and running cost are increased for the study case with emission constrain compared to that without any emission constrain. The emission reduction could be achieved by a change in generation dispatch schedules but this is obtained at the expense of fuel cost. The thermal unit commitment for the day of peak load is drawn in Figure 6 with 8% reserve and taking into account the emission constraints.

Table 2. Available reserve after UC for day of peak load

		Without emission constraint			**With emission constraint**		
Hour	**Peak Load**	**Reserve**			**Reserve**		
	MW	**None** **MW**	**≥ 5%** **MW**	**≥ 8%** **MW**	**None** **MW**	**≥ 5%** **MW**	**≥ 8%** **MW**
01	9610	17.35	498.85	798.65	83.90	486.60	774.95
02	9390	303.45	471.85	756.80	48.40	472.15	767.50
03	9130	6.00	462.40	731.00	132.90	458.55	731.10
04	9000	5.30	451.60	722.40	105.25	452.05	722.85
05	8710	8.00	440.25	708.25	74.40	439.80	709.25
06	8590	17.65	441.00	704.25	121.20	441.00	694.70
07	8730	61.80	450.85	709.05	83.30	447.10	705.10
08	9300	313.70	465.00	754.15	103.20	480.85	812.90
09	9730	188.95	487.25	830.65	88.15	490.80	901.70
10	10140	288.45	515.25	815.85	127.55	518.50	815.85
11	10435	2.05	527.60	839.55	135.75	540.20	842.90
12	10640	28.55	533.00	853.10	43.90	551.50	862.60
13	10830	5.05	545.05	883.00	45.20	558.40	883.00
14	10890	0.70	555.25	872.80	11.25	559.00	873.25
15	10890	14.95	555.25	883.00	19.95	545.05	883.00
16	10800	16.60	557.05	864.40	15.80	556.60	874.60
17	10540	17.05	535.40	849.30	89.65	542.65	859.05
18	10430	13.25	537.25	847.00	38.65	525.35	838.80
19	10470	5.05	531.00	851.05	106.90	531.00	845.25
20	10540	14.70	534.75	850.95	54.60	530.85	862.35
21	10450	16.80	529.50	842.85	51.25	528.90	843.30
22	10360	13.05	527.40	844.50	5.25	546.30	830.25
23	10210	264.60	523.80	823.05	134.70	580.85	823.05
24	9950	0.50	505.60	797.60	168.70	503.30	807.05

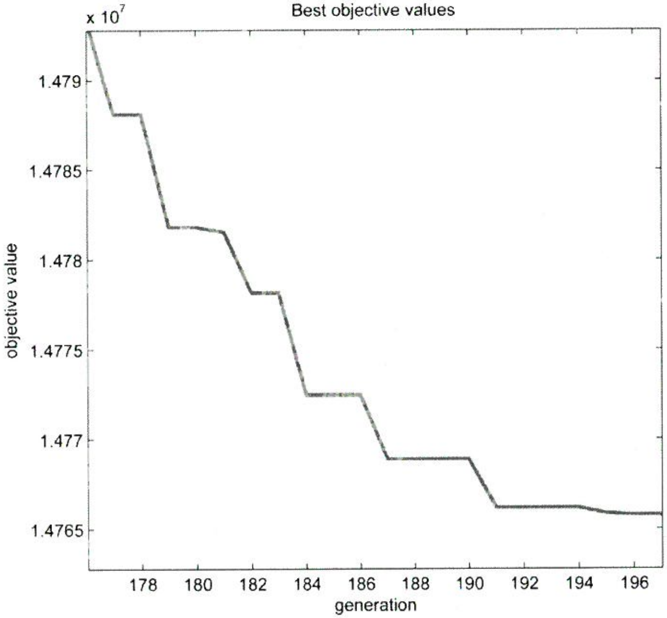

Fig. 5. Objective function vs. number of population generation

From the results displayed in Table 3 of minimum cost and minimum emission unit commitment with 8% reserve, it is observed that there is an increase in fuel cost of \$1.53029 $\times 10^6$ as a result of reduction in greenhouse gases emission. This reduction in emission could be attributed to the fact of starting gas turbines with less harmful emission compared to oil-fired units. For the day with peak load of 10,890 MW, the reduction in CO_2, NO_x and SO_x emissions are 250.61, 0.491 and 0.537 Kg, respectively. Moreover, Table 4 displays the hourly reduction of these emitted greenhouse gases.

Table 3. Total production cost for day of peak load

	Without emission constraint			With emission constraint		
Cost	Reserve			Reserve		
\$	None MW	≥ 5% MW	≥ 8% MW	None MW	≥ 5% MW	≥ 8% MW
Start up	37100	52500	53500	41900	51200	57000
Running	15.2042×10^6	15.2351×10^6	15.0934×10^6	16.8100×10^6	16.7028×10^6	16.6202×10^6
Total	15.2413×10^6	15.2876×10^6	15.1469×10^6	16.8519×10^6	16.7540×10^6	16.6772×10^6

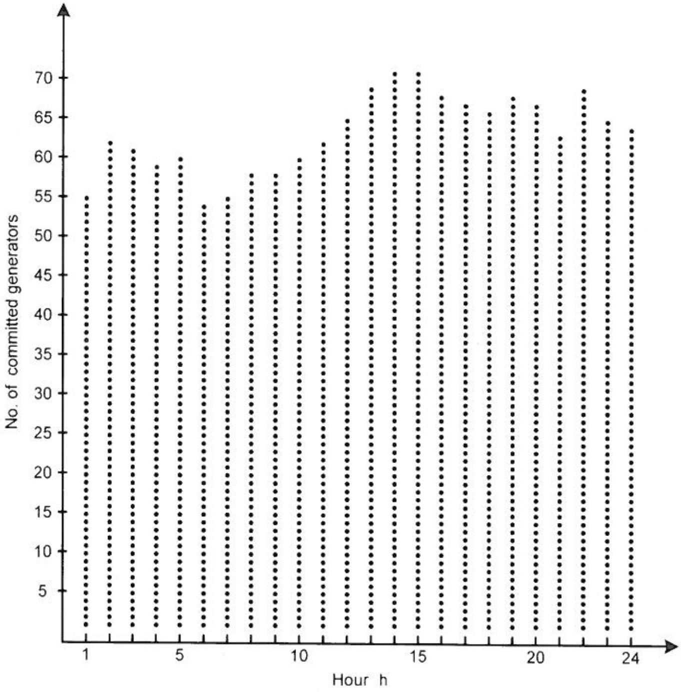

Fig. 6. Commitment status of thermal units (a filled dot means that the unit is committed)

CONCLUSIONS

Recently, environmental concern is an extremely important issue in the operational planning of the power generation systems. This paper presents an improved genetic based algorithm to deal with the emission constrained unit commitment optimization problem. A price penalty factor is defined that augments the greenhouse gases emission costs with the normal fuel cost functions. The augmented objective function includes emission price penalty in addition to the fuel cost, startup cost, and shutdown cost. This technique consists of two stages. In first stage, near feasible individuals are generated in solving economic dispatch problem. These individuals are part of the population of the first generation of GA which is applied in the second stage to identify the optimal scheduling of the generating units. In the proposed technique, individuals which do not satisfy constraints are weighted according to their distances from constraints satisfaction.

System load and unit constraints are taken into account. Generating units minimum up time, minimum down time, and generated power limits of each unit are also considered in the improved GA. Several test cases are executed on the 83 units of the generation system in Kuwait with different percentage of spinning reserve to illustrate its effect on the production, startup cost and the amount of the emitted greenhouse gases from the power plants. It is found that the proposed technique is simple, straight forward and has a good convergence property so that it could be applied to a wide range of emission constrained unit commitment problems. As a future work, the applications of the improved algorithm can be extended to include system security, transmission losses, as well as buying and selling policies between interconnected systems to reflect the real time operation in Gulf Cooperation Council (GCC) countries.

Table 4. Reduction of greenhouse gases emission using ECUC algorithm for study case with 8% reserve

Hour	Peak Load MW	CO_2 Kg	NO_x Kg	SO_x Kg
01	9610	6.59	0.003	0.004
02	9390	14.73	0.116	0.149
03	9130	5.82	0.006	0.004
04	9000	10.26	0.008	0.004
05	8710	10.55	0.007	0.004
06	8590	7.63	0.003	0.004
07	8730	7.39	0.008	0.005
08	9300	18.18	0.119	0.149
09	9730	10.68	0.004	0.005
10	10140	10.58	0.008	0.004
11	10435	7.55	0.002	0.004
12	10640	8.81	0.005	0.004
13	10830	10.92	0.009	0.004
14	10890	9.40	0.008	0.005
15	10890	10.47	0.009	0.005
16	10800	13.21	0.010	0.005
17	10540	11.88	0.010	0.004
18	10430	10.88	0.008	0.005
19	10470	10.49	0.006	0.005
20	10540	5.51	0.002	0.003
21	10450	12.61	0.009	0.005
22	10360	8.43	0.007	0.003
23	10210	11.04	0.008	0.004
24	9950	16.90	0.116	0.149
	Total:	**250.61**	**0.491**	**0.537**

Appendix

A. Coefficients of cost and emission functions

The coefficients of the fuel cost quadratic functions of generating units used in this paper are shown in Table 5. Similarly, the coefficients of the greenhouse gases emission functions of generating units (CO_2, NO_x, SO_x) are shown in Table 6, 7, and 8 respectively.

Table 5. Coefficients of Generators Fuel Cost Functions

	$	$FC_i\left(P_i^t\right)=a_i+b_i\cdot\left(P_i^t\right)+c_i\cdot\left(P_i^t\right)^2$		
		a_i	b_i	c_i
P. S.	MW		Steam Turbines	
(1)	–	–	–	–
(2)	134	3340.032	29.349	0.11733
(3)	150	2193.026	37.408	0.02163
(4)	300	2834.885	37.377	0.02519
(5)	300	2490.233	38.290	0.02044
	280	2490.233	38.290	0.02044
(6)	300	1877.950	36.043	0.02592
			Gas Turbines	
(1)	42	3299.220	51.269	0.27143
(2)	–	–	–	–
(3)	18	3489.950	66.500	0.19550
(4)	28.2	3242.255	48.087	0.03326
(5)	27.75	3242.255	48.087	0.03326
	130	3242.255	48.087	0.03326
	165	3242.255	48.087	0.03326
(6)	41.7	3242.255	48.087	0.03326
	62.5	3242.255	48.087	0.03326

Table 6. Coefficients of Generators CO2 Emission Functions

	Kg	$EC_i\left(P_i^t\right)=\gamma_i+\beta_i\cdot\left(P_i^t\right)+\alpha_i\cdot\left(P_i^t\right)^2$		
		γ_i	β_i .	α_i
P. S.	MW		Steam Turbines	
(1)	–	–	–	–
(2)	134	19.229	0.27542	0.0001732
(3)	150	32.818	0.11731	0.0002734
(4)	300	42.641	0.15902	0.0003102
(5)	300	64.699	0.10060	0.0003359
	280	64.699	0.10060	0.0003359
(6)	300	67.864	05745	0.0001942
			Gas Turbines	
(1)	42	2.739	0.04299	0.0114293
(2)	–	–	–	–
(3)	18	2.739	0.04299	0.0114293
(4)	28.2	10.541	0.14436	0.0003263
	27.75	10.541	0.14436	0.0003263
(5)	130	10.541	0.14436	0.0003263
	165	10.541	0.14436	0.0003263
(6)	41.7	10.541	0.14436	0.0003263
	62.5	10.541	0.14436	0.0003263

Table 7. Coefficients of Generators NOx Emission Functions

	Kg	$EC_i\left(P_i^t\right)=\gamma_i+\beta_i\cdot\left(P_i^t\right)+\alpha_i\cdot\left(P_i^t\right)^2$		
		γ_i	β_i	α_i
P. S.	MW		Steam Turbines	
(1)	–	–	–	–
(2)	134	0.0303165	4.14141×10^{-5}	8.82579×10^{-7}
(3)	150	0.0758209	1.98820×10^{-4}	4.30769×10^{-7}
(4)	300	0.1308619	2.25309×10^{-4}	5.32373×10^{-7}
	300	0.1755845	4.33599×10^{-4}	1.22858×10^{-6}
(5)	280	0.1755845	4.33599×10^{-5}	1.22858×10^{-6}
(6)	300	0.1689102	1.96752×10^{-4}	1.01878×10^{-6}
			Gas Turbines	
(1)	42	0.00182	1.31863×10^{-4}	5.20640×10^{-6}
(2)	–	–	–	–
(3)	18	0.00182	1.31863×10^{-4}	5.20640×10^{-6}
(4)	28.2	0.01378	8.96476×10^{-5}	2.60682×10^{-7}
	27.75	0.01378	8.96476×10^{-5}	2.60682×10^{-7}
(5)	130	0.01378	8.96476×10^{-5}	2.60682×10^{-7}
	165	0.01378	8.96476×10^{-5}	2.60682×10^{-7}
(6)	41.7	0.01378	8.96476×10^{-5}	2.60682×10^{-7}
	62.5	0.01378	8.96476×10^{-5}	2.60682×10^{-7}

Table 8. Coefficients of Generators SOx Emission Functions

	Kg	$EC_i\left(P_i^t\right)=\gamma_i+\beta_i\cdot\left(P_i^t\right)+\alpha_i\cdot\left(P_i^t\right)^2$		
		γ_i	β_i	α_i
P. S.	MW		Steam Turbines	
(1)	–	–	–	–
(2)	134	3.22440×10^{-5}	1.61047×10^{-5}	1.12391×10^{-7}
(3)	150	0.0783369	2.17919×10^{-4}	6.63298×10^{-7}
(4)	300	0.1217876	2.98855×10^{-4}	5.02404×10^{-7}
(5)	300	0.1856211	2.06674×10^{-6}	1.50579×10^{-6}
	280	0.1856211	2.06674×10^{-6}	1.50579×10^{-6}
(6)	300	0.1631352	3.56714×10^{-4}	4.28836×10^{-7}
			Gas Turbines	
(1)	42	1.65238×10^{-5}	1.67036×10^{-6}	3.62839×10^{-8}
(2)	–	–	–	–
(3)	18	1.65238×10^{-5}	1.67036×10^{-6}	3.62839×10^{-8}
(4)	28.2	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}
	27.75	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}
(5)	130	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}
	165	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}
(6)	41.7	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}
	62.5	1.44521×10^{-4}	6.85817×10^{-7}	4.05878×10^{-9}

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