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Optimal Unit Commitment with Renewable Energy in Regulated and Deregulated Systems

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Abstract

In this paper, the impact of the wind power generation system on the total cost and profit of the system is studied by using the proposed procedure of binary Sine Cosine (BSC) optimization algorithm with optimal priority list (OPL) algorithm. As well, investigate the advantages of system transformation from a regulated system to a deregulated system and the difference in the objective functions of the two systems. The suggested procedure is carried out in two parallel algorithms; The goal of the first algorithm is to reduce the space of searching by using OPL, while the second algorithm adjusts BSC to get the optimal economic dispatch with minimum operation cost of the unit commitment (UCP) problem in the regulated system. But, in the deregulated system, the second algorithm adopts the BSC technique to find the optimal solution to the profit-based unit commitment problem (PBUCP), through the fast of researching the BSC technique. The proposed procedure is applied to IEEE 10-unit test system integrated with the wind generator system. While the second is an actual system in the Egyptian site at Hurghada. The results of this algorithm are compared with previous literature to illustrate the efficiency and capability of this algorithm. Based on the results obtained in the regulated system, the suggested procedure gives better results than the algorithm in previous literature, saves computational efforts, and increases the efficiency of the output power of each unit in the system and lowers the price of kWh. Besides, in the deregulated system the profit is high and the system is more reliable.

Keywords

Profit Based Unit Commitment Problem, Binary Sine Cosine, Optimal Priority List, Regulated and Deregulated System

1. Introduction

In the past, regulated power system generation had generated power to meet their consumer's needs at the minimum cost. This means that the utility manages the unit commitment provided that each Power Load demand (PLD) and standby power are met. The optimal economical operation for the unit commitment problem (UCP) includes choosing which thermal units (TUs) are turning on/off within a certain period of time and getting the optimal output power of TUs at the lowest operating cost under various constraints of the system. There are two resolutions to resolve UCP optimizations. The first is the scheduled TUs to determine the on/off state of these units at every hour of a given time. The second is the optimal distribution of TUs committed to providing a given load while meeting the different constraints. UCP optimization is considered to be a complex problem caused by the highest dimension of possible solutions. According to this complexity, UCP is solved by various techniques.

Owing to global climate change and rising fuel prices, the rollout of renewable energy (essentially wind power) is a welcome step toward limiting pollutant emissions from conventional power plants and reducing overall operating costs. The problem with renewable power generation comes from the inherent volatility and randomness of supply. Power generation also fluctuates independently of demand. Therefore, it is becoming increasingly important to find appropriate control strategies that can effectively control and manage power production in a flexible and proactive method. Therefore, forecasting renewable energy sources is a very important task to ensure optimal utilization of the energy generated from these sources. The predicted solar radiation data is modeled using the second Markov analysis method [1].

After changing the network structure, however, it is more competitive under deregulation. In the competitive power market, the power generation units are owned by multiple generation companies and it's also called power system deregulation. Generation companies can now look at the amount of energy and reserve sold in the market. The main aims of the deregulated energy market are:

- Providing energy for all reasonable requirements.
- Encouraging the competition in the generation and supply of energy.
- Improving continuity of supply and quality of services.
- Promoting efficiency and economy of the power system.

The main objective function of a deregulated system is to maximize the total profit of the system. There are many techniques to maximize system profit, such as:

A hybrid technique consisting of Lagrangian relaxation and differential evolution was proposed in [2] to solve the profit-based unit commitment problem (PBUCP), and the results showed the quality of this technique compared to previous methods. In [3], a hybrid technique combining Lagrangian relaxation and particle swarm optimization algorithm was used to obtain the solution of generation companies' PBUCP in a deregulated system. An evolutionary particle swarm optimization technique has been proposed to resolve PBUCP for generation companies in deregulated markets. The formulation of this problem includes a constraint that specifies the minimum generation company production for a given hour as the hourly bilaterally committed generation [4]. The genetic algorithm based on the priority list has been used to solve unit commitment and economic load in the case of TUs combined with solar and wind energy. The integration of renewables reduces the overall cost of operating electricity but adds additional services to offset power imbalances caused by uncertainties in renewables or loads [5]. The integration of both photovoltaic and wind turbines at unit commitment was investigated with the power system and a risk-reducing solution to the problem was investigated. Owing to the Sharing of photovoltaic and wind systems, the goal is to obtain the on/off state as well as the output power of all thermal units at the lowest operating cost through the scheduling time, depending on the system constraints. Using the probabilistic method of the confidence interval. Uncertainties in wind power and photovoltaics were modeled by error analysis of expected wind speed and solar predicted radiation data. Differential evolution algorithms for the uncertainty were presented to get the solution to the two-stage mixed-integer nonlinear optimization problem [6]. The hybrid technique of the levy flight search technique with the non-dominated sorting of moth fly optimization was presented in [7] to maximize revenue-generating companies and total fuel cost in light of mandate strength measurement estimates, and power reserve with or without wind power. The computational time of this technique is reduced and leads to profit maximization. Numerical results show this with non-specific information about photovoltaic and wind power. By taking into account the reliable rated power generation of photovoltaic and wind turbines, it is possible to reliably schedule other units one day in advance. An Exchange Market algorithm [8] was used to solve PBUCP and was applied to the IEEE 10 unit test system. The results of the Exchange Market algorithm were compared with other algorithms in the literature. Comparisons of this approach concluded that the Exchange Market algorithm is more efficient for solving PBUC in a deregulated market. Reducing the total operating cost of TUs to get maximum profit for generation companies is named the optimal ahead-day scheduling problem. Furthermore, it is realistic to redefine this problem to include many distributed resources and electric vehicles with energy storage. A new approach was used to deal with PBUCP, taking into consideration the power and standby conditions [9]. The proposed method allows generation companies to determine the amount of energy and reserve that must be sold in the markets to achieve maximum profit.

The parallel binary sine cosine with an optimal priority list algorithm was used to solve the UCP in a regulated system [10]. The results showed the capability and efficiency of this algorithm. According to these results, this parallel algorithm is used in this paper to solve the UCP & PBUCP, which are integrated with wind energy generation systems in a regulated and a deregulated system respectively.

In this paper, the regulated and deregulated systems are introduced and the objective function of both systems is applied to IEEE 10-units test system integrated with wind energy (actual site in Egypt).

This paper contains five sections. The first section contains the introduction to the subject of research. The second section contains the formulation of regulated and deregulated system and the wind energy generation system studying. The third section contains the regulated and deregulated methodologies. The fourth section illustrates the application of the IEEE 10-units test system integrated with wind energy generation system and the fifth section illustrates the conclusion of this paper.

2. Formulation of Regulated and Deregulated Power Systems

UCP in the regulated and PBUCP in the deregulated power systems include the on/off of the thermal units for a specific hour of predicted load, taking into account both wind power generation ($\mathcal{P}_{\mathcal{W}g}$) and PLD. The decision of the UCP involves different constraints, such as generation -load demand balance, thermal unit constraints, minimum start-up, downtime, spinning reserve, and thermal unit initial state. After the UCP is decided, the ELD is applied to the committed thermal units to determine output power per unit committed. What was mentioned before is to find the optimal total cost of electricity generation with all the different constraints met. The PBUCP consists of the committee assignment and the generation assignment through generation companies as the price receiver. The aim of PBUCP is to minimize the total operation cost by maximizing the total profit of generation companies.

2.1. Single Objective Function of UCP in the Regulated System

The main objective function of a UCP solution in a regulated power system is to minimize the total operating cost ($\mathcal{T}_{\propto}$). It must be identified when all the constraints of equality and inequality are met. Then, the scheduling of all TUs across the scheduled time horizon is as follows [11]:

$$Min\left(\mathcal{T}_{\propto}\right)=\sum_{\mathcal{T}=1}^{\mathcal{T}_{\mathcal{S}}}\sum_{\mathrm{n}=1}^{\mathcal{K}}\left[\left[\mathcal{F}_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)+\mathcal{ST}_{\mathrm{n},\mathcal{T}}\left(1-\mathcal{U}_{\mathrm{n},\mathcal{T}-1}\right)\mathcal{U}_{\mathrm{n},\mathcal{T}}\right]+\mathcal{SD}_{\mathrm{n}}\left(1-\mathcal{U}_{\mathrm{n},\mathcal{T}}\right)\mathcal{U}_{\mathrm{n},\mathcal{T}-1}\right] \quad (1)$$

where,

$\mathcal{T}_{\propto}$: Total operation cost of the generation system during overall scheduling period time.

$\mathcal{T}_{\mathcal{S}}$: Overall scheduling period time.

$\mathcal{T}$: Period time index.

$\mathcal{K}$: Numbers of overall thermal units.

$\mathcal{F}_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)$: Function of fuel cost thermal unit (n) at time period ($\mathcal{T}$).

n: Index of thermal unit.

$\mathcal{ST}_{\mathrm{n},\mathcal{T}}$: Thermal unit (n) at time ($\mathcal{T}$) starting cost.

$\mathcal{U}_{\mathrm{n},\mathcal{T}}, \mathcal{U}_{\mathrm{n},\mathcal{T}-1}$: Status of thermal unit (n) at time ($\mathcal{T}$) and time ($\mathcal{T}-1$) for the unit operated on or off.

2.2. Single Objective Function of PBUCP in the Deregulated Power System

PBUCP is a multi-objective nonlinear optimization problem that involves the instantaneous optimization of generation companies, while all equal and unequal constraints are met. The first function is revenue and the second is the total cost. Then, scheduling the generation of all TUs over a horizontal time period is defined as [7]:

$$Max\left(\mathcal{PF}\right)=\mathcal{RV}-\mathcal{T}_{\propto} \tag{2}$$

$$\begin{aligned}\mathcal{T}_{\propto}=\sum_{\mathcal{T}=1}^{\mathcal{T}_{\mathcal{S}}}\sum_{\mathrm{n}=1}^{\mathcal{K}}\Big[\Big[\left(1-\mathcal{R}\right)\mathcal{F}_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)+\mathcal{R}\mathcal{F}_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}+\mathcal{Y}_{\mathrm{n},\mathcal{T}}\right)+\mathcal{ST}_{\mathrm{n},\mathcal{T}}\left(1-\mathcal{U}_{\mathrm{n},\mathcal{T}-1}\right)\mathcal{U}_{\mathrm{n},\mathcal{T}}\Big] \\ +\mathcal{SD}_{\mathrm{n}}\left(1-\mathcal{U}_{\mathrm{n},\mathcal{T}}\right)\mathcal{U}_{\mathrm{n},\mathcal{T}-1}\Big]+\sum_{\mathcal{T}=1}^{\mathcal{T}_{\mathcal{S}}}\sum_{\mathrm{i}=1}^{\mathrm{n}_{\mathcal{W}}}\mathcal{P}_{\mathcal{W}\mathrm{g}}\left(\mathrm{i},\mathcal{T}\right)*\mathcal{W}\mathrm{oc}\end{aligned} \tag{3}$$

$$\mathcal{RV}=\sum_{\mathcal{T}=1}^{\mathcal{T}_{\mathcal{S}}}\sum_{\mathrm{n}=1}^{\mathcal{K}}\Big[\Big[\mathcal{SP}_{\mathrm{n}\mathcal{T}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)+\left(\left(1-\mathcal{R}\right)*\mathcal{RP}_{\mathrm{n},\mathcal{T}}+\mathcal{R}*\mathcal{SP}_{\mathrm{n}\mathcal{T}}\right)\mathcal{Y}_{\mathrm{n},\mathcal{T}}\Big]\mathcal{U}_{\mathrm{n},\mathcal{T}}\Big] \tag{4}$$

$$\mathcal{F}_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)=\Upsilon_{\mathrm{n}}\left(\mathcal{P}_{\mathrm{n},\mathcal{T}}\right)^{2}+\beta_{\mathrm{n}}\mathcal{P}_{\mathrm{n},\mathcal{T}}+\alpha_{\mathrm{n}} \tag{5}$$

where,

$Max\left(\mathcal{PF}\right)$: Maximum profit.

$\mathcal{RV}$: Total cost of revenue.

$\mathcal{T}_{\propto}$: Total Operating Cost

$\Upsilon_{\mathrm{n}},\beta_{\mathrm{n}},\alpha_{\mathrm{n}}$: Cost coefficients of thermal unit (n).

$\mathcal{P}_{\mathrm{n},\mathcal{T}}$: Power output of thermal unit (n) at time ($\mathcal{T}$).

$\mathcal{SD}_{\mathrm{n}}$: Thermal unit ($\mathrm{n}$) shut down cost.

i: Number of total Wind generator units.

$\mathrm{n}_{\mathcal{W}}$: Wind generator index unit.

$\mathcal{W}\mathrm{oc}$: Wind operational cost.

$\mathcal{P}_{\mathcal{W}\mathrm{g}}\left(\mathrm{i},\mathcal{T}\right)$: Wind energy output of unit (i) at time ($\mathcal{T}$).

$\mathcal{R}$: Probability of the reserve is generated.

$\mathcal{Y}_{\mathrm{n},\mathcal{T}}$: Reserve generation of generator (n) at time ($\mathcal{T}$).

$\mathcal{SP}_{\mathrm{n},\mathcal{T}}$: Forecasted spot price at hour.

$\mathcal{RP}_{\mathrm{n},\mathcal{T}}$: Forecasted reserve price at hour.

The start-up cost of TUs (n) is determined by time, the decommissioning of TUs to operate is as follows [12]:

$$\mathcal{ST}_{\mathrm{n},\mathcal{T}}=\begin{cases}\mathcal{SH}_{\mathrm{n}} & \mathcal{T}_{\mathrm{n},down}\le\mathcal{T}_{\mathrm{n}}^{off}\left(\mathcal{T}\right)\le\mathcal{H}_{\mathrm{n}}^{off} \\ \mathcal{S}\mathrm{c}_{\mathrm{n}} & \mathcal{T}_{\mathrm{n}}^{off}>\mathcal{H}_{\mathrm{n}}^{off}\end{cases} \tag{6}$$

$$\mathcal{H}_{\mathrm{n}}^{off}=\mathcal{T}_{\mathrm{n},down}+\mathcal{T}_{\mathrm{n}}^{cold} \tag{7}$$

where,

$\mathcal{SH}_{\mathrm{n}}$: Hot startup cost of thermal unit (n).

$\mathcal{S}\mathrm{c}_{\mathrm{n}}$: Cold startup cost of thermal unit (n).

$\mathcal{T}_{\mathrm{n},down}$: Minimum down time of thermal unit (n).

$\mathcal{T}_{\mathrm{n}}^{off}\left(\mathcal{T}\right)$: Continuously off time of thermal unit (n) at time ($\mathcal{T}$).

$\mathcal{T}_{\mathrm{n}}^{cold}$: Starting cold time of thermal unit (n).

$\mathcal{H}_{\mathrm{n}}^{off}$: Sum of cold start time and minimum thermal unit (n) downtime.

The main objective function of regulated and deregulated system is applied under the following constraints:

- The equal constraints

1) Balance the power generation system

All power output of TUs and wind generator operated on must be meeting the PLD as [13]:

$$\mathcal{P}_{\mathrm{d},\mathcal{T}} = \sum_{\mathrm{n}=1}^{\mathcal{K}} \mathcal{P}_{\mathrm{n},\mathcal{T}} \mathcal{U}_{\mathrm{n},\mathcal{T}} + \mathcal{P}_{\mathcal{W}\mathrm{g}}\left(\mathrm{i},\mathcal{T}\right) \tag{8}$$

where,

$\mathcal{P}_{\mathrm{d},\mathcal{T}}$: Power load demand at time ($\mathcal{T}$).

- The unequal constraints

1) Spinning power reserve requirement

The Spinning power reserve is essential in the operation of the power system and is determined as a sufficient percentage of the PLD as follows [14] [15]:

$$\mathcal{P}_{\mathrm{d},\mathcal{T}} + \mathcal{P}_{\mathrm{r},\mathcal{T}} \le \sum_{\mathrm{n}=1}^{\mathcal{K}} \mathcal{P}_{\mathrm{n},\mathcal{T}} \mathcal{U}_{\mathrm{n},\mathcal{T}} \tag{9}$$

where,

$\mathcal{P}_{\mathrm{r},\mathcal{T}}$: Spinning power reserve at time ($\mathcal{T}$).

2) Limits of thermal units

All TUs have power generation bands ($\mathcal{P}_{\mathrm{n},\mathcal{T}}$) which are mentioned as follows [16]:

$$\mathcal{P}_{\mathrm{n,min}} \le \mathcal{P}_{\mathrm{n},\mathcal{T}} \le \mathcal{P}_{\mathrm{n,max}} \tag{10}$$

where,

$\mathcal{P}_{\mathrm{n,min}}$: Minimum generation power limit of thermal unit (n).

$\mathcal{P}_{\mathrm{n,max}}$: Maximum generation power limit of thermal unit (n).

3) Minimum up time for TUs

TUs must be turned on at a certain hour before being shut down as [17]:

$$\mathcal{T}_{\mathrm{n}}^{on}\left(\mathcal{T}\right) \ge \mathcal{T}_{\mathrm{n}}^{up} \tag{11}$$

where, $\mathcal{T}_{\mathrm{n}}^{on}\left(\mathcal{T}\right)$: Continuously on time of thermal unit (n) at time ($\mathcal{T}$).

$\mathcal{T}_{\mathrm{n}}^{up}$: Minimum on time of thermal unit (n).

4) Minimum down time for TUs [18].

TUs must be turned off for a certain hour before they can be turned on.

$$\mathcal{T}_{\mathrm{n}}^{off}\left(\mathcal{T}\right) \ge \mathcal{T}_{\mathrm{n},down} \tag{12}$$

5) TUs initial states [19].

The initial thermal state condition must be satisfied in the case in period.

2.3. Calculation of Wind Energy Generation System

The output of the wind energy generation system depends on three elements. The first is the meteorological conditions at the installation site, such as wind speed and its direction, temperature, and atmospheric pressure [20] [21]. The second is followed by the characteristics of the wind turbine, such as type, diameter, rotational speed (rpm) and coefficient of performance. Third is a generator characteristic such as type and rate, efficiency, cut-in wind speed, rated wind speed, and cut-out wind speed [22]. However, $\mathcal{P}_{\mathcal{W}\text{g}}$, is dependent on the power speed characteristics of the wind generator mode. This power can be modeled as [23]:

$$\mathcal{P}_{\mathcal{W}\text{g}} = \begin{cases} 0 & \mathcal{V}_{\text{ci}} > \mathcal{V}_{\text{i}}, \mathcal{V}_{\text{i}} > \mathcal{V}_{\text{co}} \\ \mathcal{K}_{\mathcal{W}\text{g}} * \mathcal{V}_{\text{i}}^3 & \mathcal{V}_{\text{ci}} \le \mathcal{V}_{\text{i}} \le \mathcal{V}_{\text{r}} \\ \mathcal{P}_{\text{r}} & \mathcal{V}_{\text{r}} \le \mathcal{V}_{\text{i}} \le \mathcal{V}_{\text{co}} \end{cases} \tag{13}$$

$$\mathcal{E}_{\mathcal{W}\text{g}} = \begin{cases} 0 & \mathcal{V}_{\text{ci}} > \mathcal{V}_{\text{i}}, \mathcal{V}_{\text{i}} > \mathcal{V}_{\text{co}} \\ \mathcal{K}_{\mathcal{W}\text{g}} * \mathcal{T}_i * \mathcal{V}_{\text{i}}^3 & \mathcal{V}_{\text{ci}} \le \mathcal{V}_{\text{i}} \le \mathcal{V}_{\text{r}} \\ \mathcal{T}_{\text{r}} * \mathcal{P}_{\text{r}} & \mathcal{V}_{\text{r}} \le \mathcal{V}_{\text{i}} \le \mathcal{V}_{\text{co}} \end{cases} \tag{14}$$

$$\mathcal{K}_{\mathcal{W}\text{g}} = 0.5 * \rho * c_{\mathcal{P}} * \mathcal{A}_{\mathcal{T}} * \eta_{\text{m}} * \eta_{\text{g}} \tag{15}$$

where,

$\mathcal{V}_{\text{ci}}$: Cut-in wind speeds of the wind generator.

$\mathcal{V}_{\text{r}}$: Rated wind speeds of the wind generator.

$\mathcal{V}_{\text{co}}$: Cut-out wind speeds of the wind generator.

$\mathcal{V}_{\text{i}}$: Instantaneous wind speed at the hub height of the wind turbine.

$\mathcal{E}_{\mathcal{W}\text{g(a)}}$:The annual generation of this wind generator mode.

ρ: Air density.

$c_{\mathcal{P}}$: Performance coefficient of the wind turbine.

$\mathcal{A}_{\mathcal{T}}$: Swept area of wind turbine.

η_m, η_g: Efficiencies of the mechanical interface system and the wind generator.

$\mathcal{T}_i$ & $\mathcal{T}_{\text{r}}$: Duration hours of $\mathcal{V}_{\text{i}}$ though a day, month and year.

- Technical Optimization Model:

The technical optimization is modeled on the amount of electricity generated per square meter of area swept by the wind turbine.

$$\sigma\left(\mathcal{E}_{\mathcal{W}\text{g}}\right) = \mathcal{E}_{\mathcal{W}\text{g(a)}} / \mathcal{A}_{\mathcal{T}} \tag{16}$$

where, $\sigma\left(\mathcal{E}_{\mathcal{W}\text{g}}\right)$ is the annual generations per unit area of a wind generator mode.

- Economical Optimization Model:

The economy of a wind generator can be developed as a function of the capital cost of the wind energy generation system used, the annual operation and maintenance costs and the unit energy cost of generated energy of this wind energy generation system. The capital cost of a wind generator ($\mathcal{CC}_{\mathcal{W}\text{g}}$) is usually expressed in terms of its rated power or the swept area of its wind turbine as follow [24]:

$$\mathcal{CC}_{\mathcal{W}\text{g}} = \mathcal{C}_{\mathcal{W}} * \mathcal{A}_{\mathcal{T}} = \mathcal{C}_{\mathcal{PP}} * \mathcal{P}_{\text{r}} \tag{17}$$

where,

C_{pp} : Cost per 1 kW of the rated power $\mathcal{P}_r$

$\mathcal{C}_{\mathcal{W}}$: Costs per 1 m^2 of the wind turbine swept area $\mathcal{A}_{\mathcal{T}}$.

The annual capital cost ($\mathcal{ACC}_{\mathcal{W}g}$) can be estimated as:

$$\mathcal{ACC}_{\mathcal{W}g} = \mathcal{D}_r * \mathcal{CC}_{\mathcal{W}g} \tag{18}$$

where, $\mathcal{D}_r$ is the annual discount rate and given by [25]:

$$\mathcal{D}_r = r(1+r)^{ns} \Big/ \left[(1+r)^{ns} - 1\right] \tag{19}$$

And r is the interest rate and ns is the life—time of the wind generator.

Annual operation and maintenance cost of the wind generator ($\mathcal{AOC}_{\mathcal{W}g}$) is very small and can be expressed as a percentage of the annual capital cost or in ¢/ kWh of the annual generated energy. Thus, the total annual cost ($\mathcal{TAC}_{\mathcal{W}g}$) and the unit energy cost ($\mathcal{UEC}_{\mathcal{W}g}$) of a wind generator are given as [26] [27]:

$$\mathcal{TAC}_{\mathcal{W}g} = \mathcal{ACC}_{\mathcal{W}g} + \mathcal{AOC}_{\mathcal{W}g} \tag{20}$$

$$\mathcal{UEC}_{\mathcal{W}g} = \mathcal{TAC}_{\mathcal{W}g} \Big/ \mathcal{E}_{\mathcal{W}g(a)} \tag{21}$$

3. Parallel BSC-OPL Algorithm for Solving UCP in Regulated System and PBUCP in Deregulated System

In this paper, UCP in a regulated system and PBUCP in the deregulated system are solved using parallel BSC-OPL. The first algorithm, OPL, is used to rank TUs based on their unit cost of generating them. OPL is based on fuel cost (FC) [10], which (ψ) is calculated as the average differential rate of fuel cost at maximum power per TU divided by maximum power. ψ per unit is the cost per TU ($/MW) is determined as:

$$\psi_n = (2\gamma_n + \beta_n) \big/ P_{n,\max} \tag{22}$$

The second algorithm is BSC which is used to find scheduled TUs and their output power, the minimum cost in a regulated system, and maximum profit in a deregulated system. Based on the solution of UCP and PBUCP, it is required to convert the continuous Sin Cosine algorithm to zero and one. In zero and one transformation, the position of the search agents and the search space are modeled and expressed as [28]:

$$X_{i,t,n}^{(k+1)} = \begin{cases} X_{i,t,n}^{k} + \lambda 1 \times \mathrm{Sin}\lambda 2 \times \left|\lambda 3 Q^{K} - X_{i,t,n}^{k}\right| & \lambda 4 < 0.5 \\ X_{i,t,n}^{k} + \lambda 1 \times \mathrm{Cosine}\lambda 2 \times \left|\lambda 3 Q^{K} - X_{i,t,n}^{k}\right| & \lambda 4 > 0.5 \end{cases} \tag{23}$$

$$\lambda 1 = q - \frac{kq}{KK}$$

where

$X_{i,t,n}^{k}$: Position of agent i at iteration k.

$\lambda 1, \cdots, \lambda 5$: Probability of contingency occurrence.

Q^{K} : Destination position during iteration k^{th}.

$X_{i,t,n}^{(k+1)}$: Position of agent i at iteration $(k+1)$.

q: Selected fixed numbers with ranges of sine and cosine functions.

KK: Iterations number.

k: Index of iteration.

The operation mechanism of BSC is illustrated in [28] [29]. By solving the UCP and PBUCP in parallel with OPL and BSC, **Figure 1** shows the flow chart of the parallel BSC-OPL algorithm.

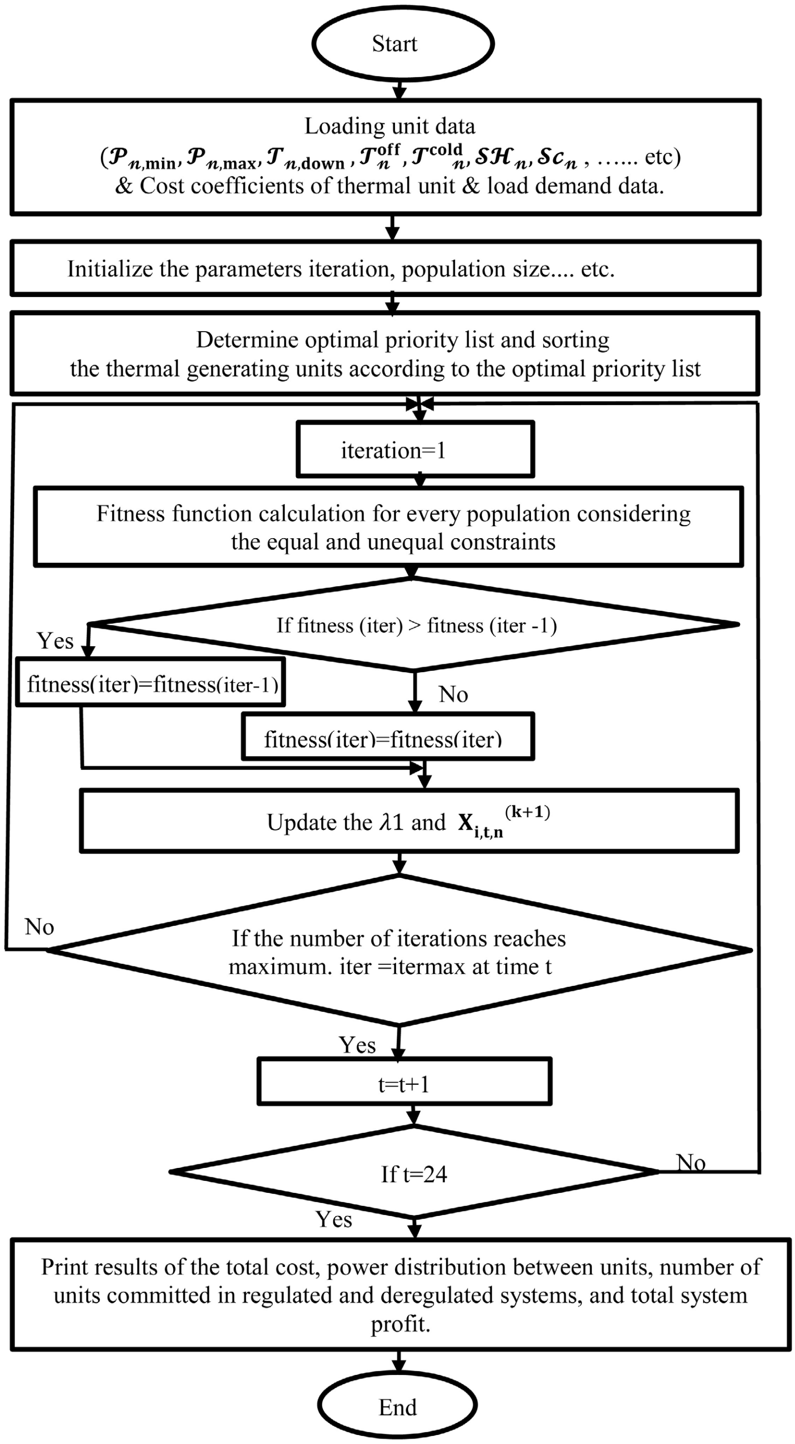

Figure 1. The flow diagram of the parallel BSC-OPL algorithm.

4. Application

In this section, a numerical study using the parallel BSC-OPL algorithm is first applied to an IEEE 10-unit test system combined with a wind power generation system consisting of 20 similar wind turbines operating in parallel [30]. **Figure 2** shows the daily load demand and generation curves for wind power generation, which are determined by previously expected wind power generation and converted to electric power. The minimum output power provided by the wind farm is 15 MW, but the maximum output power is equal to 100 MW. The result of the parallel BSC-OPL algorithm is comprised of the results obtained in [30] to determine the optimal algorithm. A parallel algorithm is introduced to obtain the minimum value of the total cost of the operation and has an economic load. **Table A1** shows the characteristics and cost coefficients for IEEE 10-units test system, while **Table A2** illustrates the PLD for a specific period (24 hours).

Second, the parallel BSC-OPL algorithm is applied to IEEE 10-units test system combined with an actual wind farm consisting of a similar type of 35 * 3000 kW wind turbine generators running in parallel and installed in the Egypt site (Hurghada). The procedure presented here is to obtain the minimization value of the total operating cost and the maximization of the total profit of generation companies and obtain the economic load.

- Parallel BSC-OPL algorithm

The parallel BSC-OPL algorithm is applied to the IEEE 10-unit test system with integrated wind power generation with different penetration levels to obtain the optimal economic load scheduling and the optimal total operating cost. Different penetration output power limits of thermal generating units are applied to increase the operating life of the TU. **Table 1** shows the optimal economic load dispatch of an IEEE 10-units test system integrated with one wind farm without thermal generation units limit in a regulated system. The results of

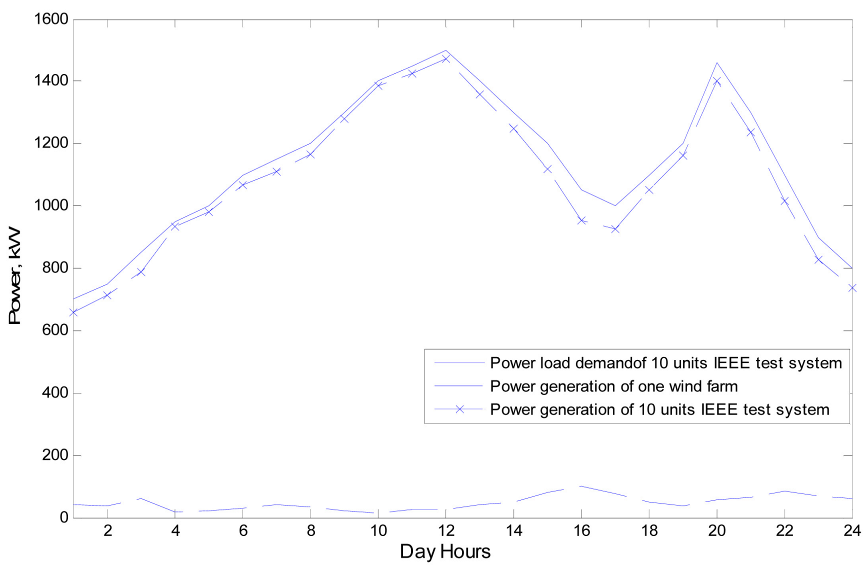

Figure 2. The daily load demand and generation curves of wind power generation [16].

Table 1. Output power of unit commitment with one wind farm for parallel BSC-OPL algorithm without thermal generation limit in regulated system.

Hour	PLD	TU_1	TU_2	TU_3	TU_4	TU_5	TU_6	TU_7	TU_8	TU_9	TU_{10}
1.0	700	455.0	202.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.0	750	455.0	259.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.0	850	455.0	335.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.0	950	455.0	452.80	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.0	1000	455.0	455.0	70.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.0	1100	455.0	455.0	28.70	0.00	130.00	0.00	0.00	0.00	0.00	0.00
7.0	1150	455.0	455.0	70.00	0.00	130.00	0.00	0.00	0.00	0.00	0.00
8.0	1200	455.0	427.20	25.00	130.00	130.00	0.00	0.00	0.00	0.00	0.00
9.0	1300	455.0	455.0	88.20	130.00	130.00	20.00	0.00	0.00	0.00	0.00
10	1400	455.0	455.0	162.00	130.00	130.00	28.00	25.00	0.00	0.00	0.00
11	1450	455.0	455.0	162.00	130.00	130.00	58.60	25.00	10.00	0.00	0.00
12	1500	455.0	455.0	162.00	130.00	130.00	80.00	25.00	25.90	10.00	0.00
13	1400	455.0	455.0	143.80	130.00	130.00	20.00	25.00	0.00	0.00	0.00
14	1300	455.0	455.0	162.00	0.00	130.00	0.00	25.00	22.50	0.00	0.00
15	1200	455.0	455.0	80.00	0.00	130.00	0.00	0.00	0.00	0.00	0.00
16	1050	455.0	341.40	25.00	0.00	130.00	0.00	0.00	0.00	0.00	0.00
17	1000	455.0	314.40	25.00	0.00	130.00	0.00	0.00	0.00	0.00	0.00
18	1100	455.0	420.30	25.00	0.00	130.00	20.00	0.00	0.00	0.00	0.00
19	1200	455.0	403.60	25.00	130.00	130.00	20.00	0.00	0.00	0.00	0.00
20	1460	455.0	455.00	162.00	130.00	130.00	45.80	25.00	0.00	0.00	0.00
21	1300	455.0	455.00	0.00	130.00	130.00	40.80	25.00	0.00	0.00	0.00
22	1100	455.0	404.00	0.00	130.00	0.00	0.00	25.00	0.00	0.00	0.00
23	900	455.0	244.30	0.00	130.00	0.00	0.00	0.00	0.00	0.00	0.00
24	800	455.0	283.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total cost = 5.3681 * 10^5 $.											

Table 1 illustrate that the total cost of this system is 5.3681 * 10^5 $. Where **Table 2** shows the effect of 3% limits of TU and the increase in penetration level of wind power generation on the total operation cost.

By comparing the results shown in **Table 2**, we can see that the parallel BSC-OPL algorithm is the best technique because it saves $18,615 (335,070 L.E) in annual fuel costs.

Figure 3 illustrates the fitness function of the Parallel BSC-OPL algorithm in the case of different thermal generation limit integrated with one wind farm. While, **Figure 4**. The fitness function of the proposed parallel BSC-OPL algorithm

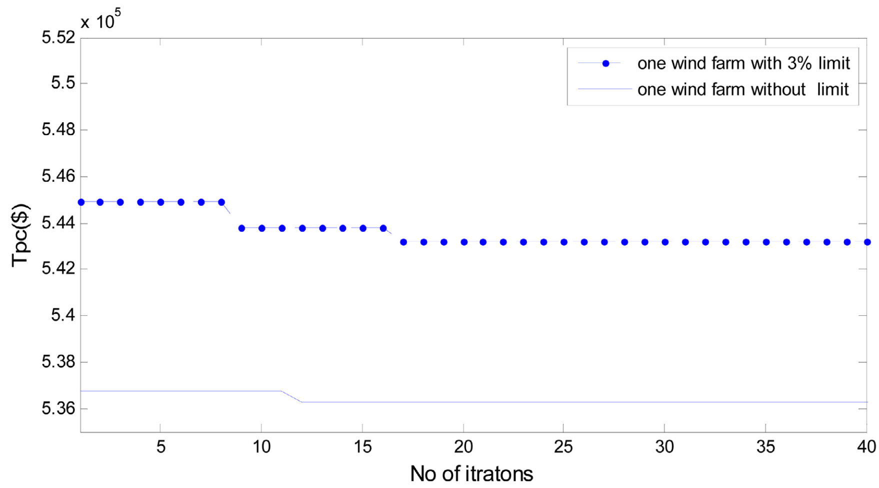

Figure 3. Variations of total cost of unit commitment with one wind farm that is determined by parallel BSC-OPL algorithm without and with 3% thermal generation limit against number of iterations in regulated system.

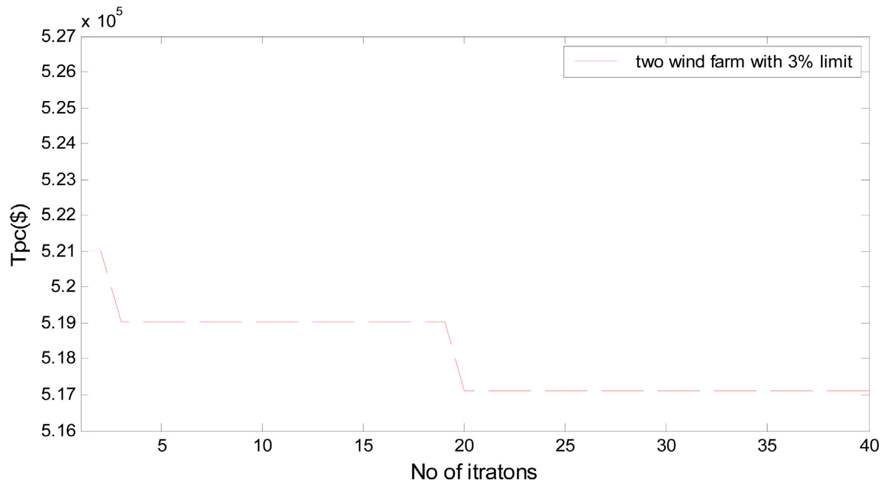

Figure 4. Variations of total production cost of unit commitment with two wind farm that is determined by parallel BSC-OPL algorithm with 3% thermal generation limit against number of iterations in regulated system.

Table 2. A comparison of parallel BSC-OPL with another algorithm.

Methods	Without limits	With 3% limits
Parallel BSC-OPL algorithm	$5.3681 * 10^5$	$5.4318 * 10^5$
Grey Wolf algorithm [30].	-	$5.43692 * 10^5$

is shown when IEEE 10-units test systems are integrated with two wind farms. **Figure 5** shows the daily power generation curve of IEEE 10-units test systems integrated with a wind farm, where 3% of the thermal power generation is limited in the regulation system. Where **Figure 6** shows the configuration of the daily generation curve of the IEEE 10-test system integrated with a wind farm with a 3% thermal generation limit.

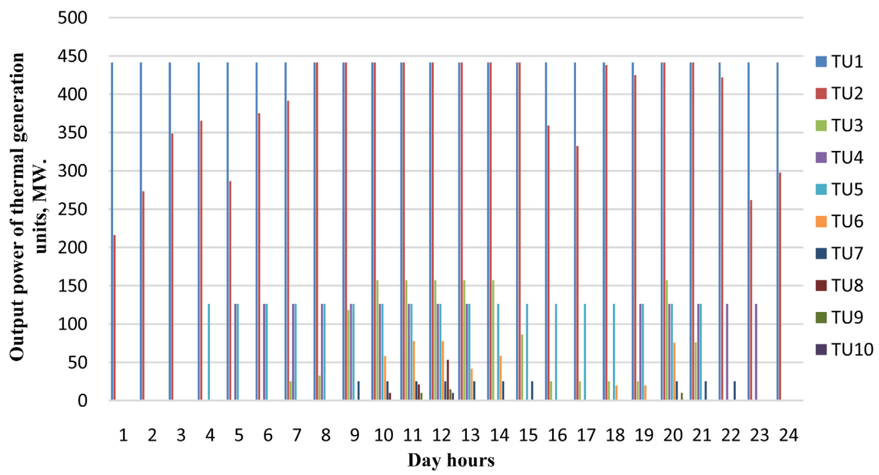

Figure 5. The daily generation curve of IEEE 10-units test system integrated with one wind farm with 3% thermal generation limits in regulated system.

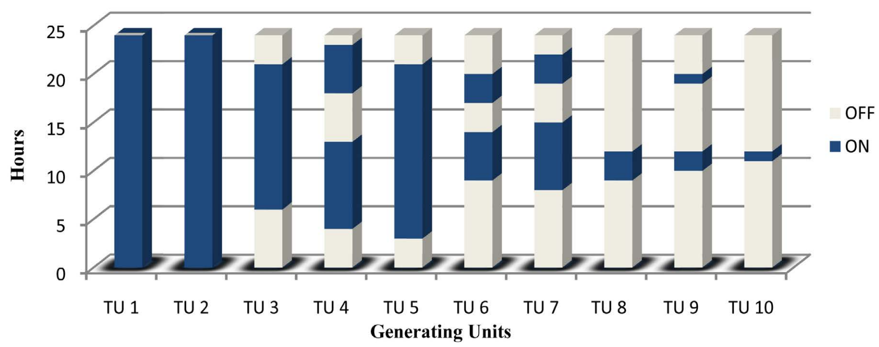

Figure 6. Configuration of unit commitment with one wind farm problem with 3% thermal generation units limit using parallel BSC-OPL algorithm in regulated system.

According to increase the penetration level of wind power generation on the system, **Figure 7** shows the daily generation curve of IEEE 10-units test system integrated with two wind farms with 3% thermal generation limits. **Figure 8** shows the configuration of unit commitment with two wind farm problems with 3% thermal generation units limits using parallel BSC-OPL algorithm.

The proposed algorithm is used to solve the PBUCP in a deregulated system. It is applied to the IEEE 10 units -test system without integrating wind energy generation systems. The obtained results were compared with previous literature results. **Table 3** shows this comparison and concludes that the proposed algorithm has the best profit.

Based on previous results, the proposed algorithm is applied to an IEEE 10-unit test system integrating with actual wind energy generation system installed at the Egyptian site (Hurghada), the recorded wind speed data of this site are used to deduce $\mathcal{V}_i$ at the hub height of the study wind generator modes (1500, 2000, 3000 kW). Characteristics of different wind generator modes [31] were used to determine $\mathcal{P}_{\mathcal{W}g}$ by day in the different seasons at the Hurghada site. **Figures 9-11**. show the average daily wind speed curve through the year seasons

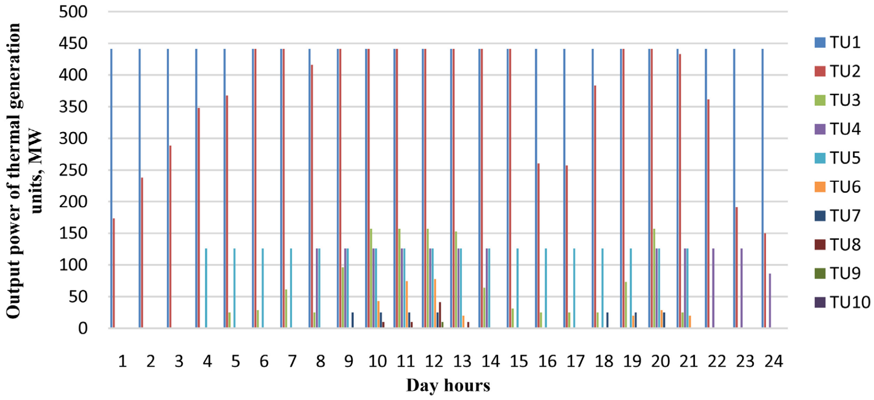

Figure 7. The daily generation curve of IEEE 10-units test system integrated with two wind farms with 3% thermal generation limits.

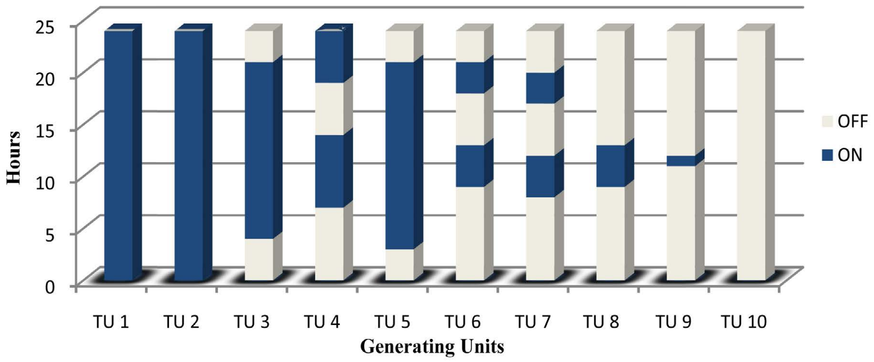

Figure 8. Configuration of unit commitment with two wind farm problem with 3% thermal generation units limit using parallel BSC—OPL algorithm.

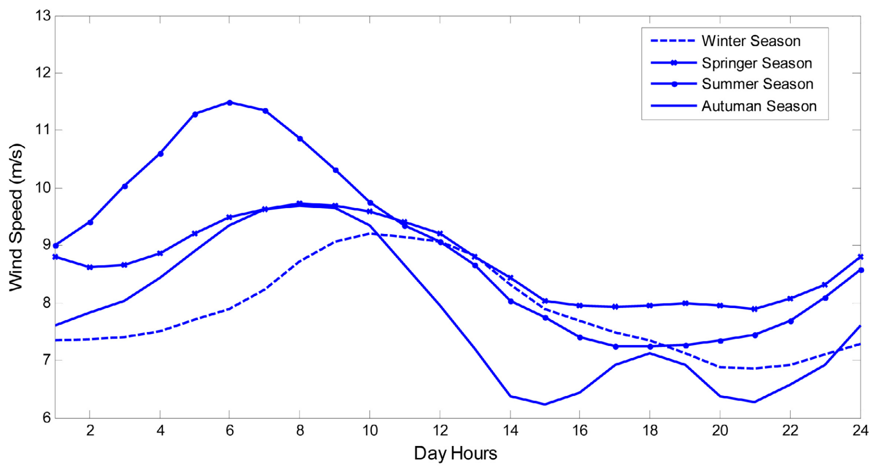

Figure 9. Average daily wind speed duration curve of (1500) kW-wind generator mode through different seasons for Hurghada site.

at the hub height of 1500, 2000, 3000 kW-wind generator mode installed at Hurghada site, respectively. While, **Figures 12-14** show the daily output wind power duration curve at the hub height of 1500, 2000, 3000 kW-wind generator mode through different seasons.

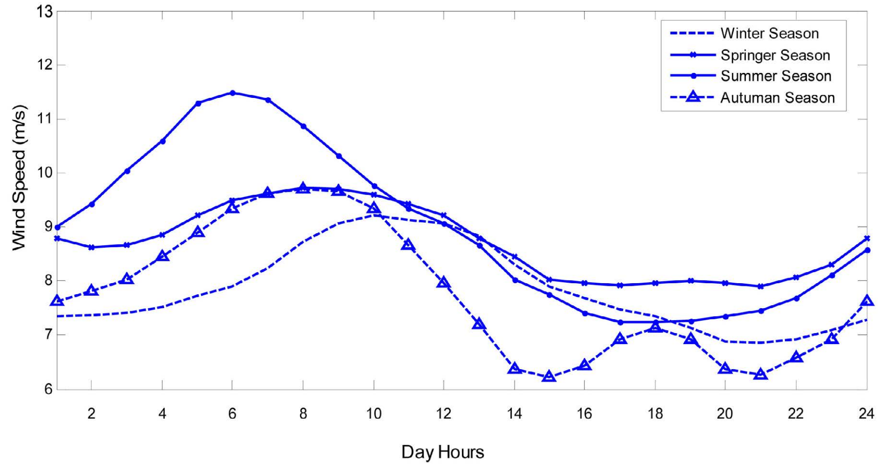

Figure 10. Average daily wind speed duration curve of (2000) kW-wind generator mode through different seasons for Hurghada site.

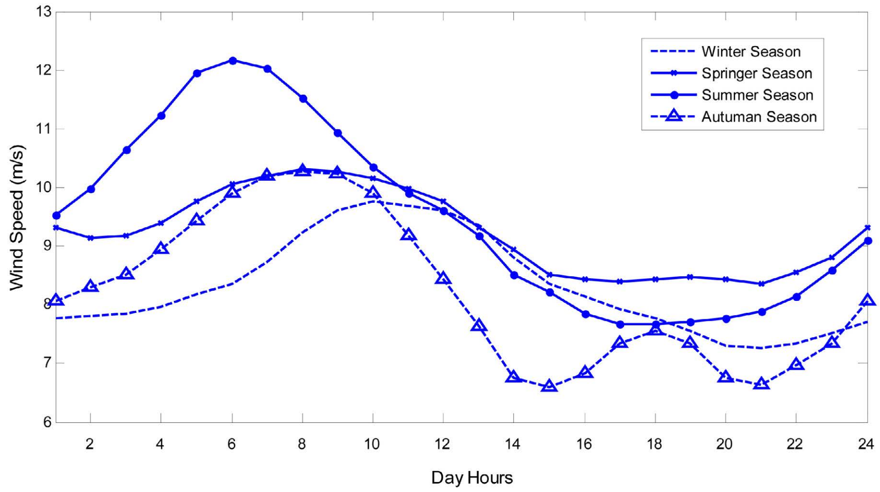

Figure 11. Average daily wind speed duration curve of (3000) kW-wind generator mode through different seasons for Hurghada site.

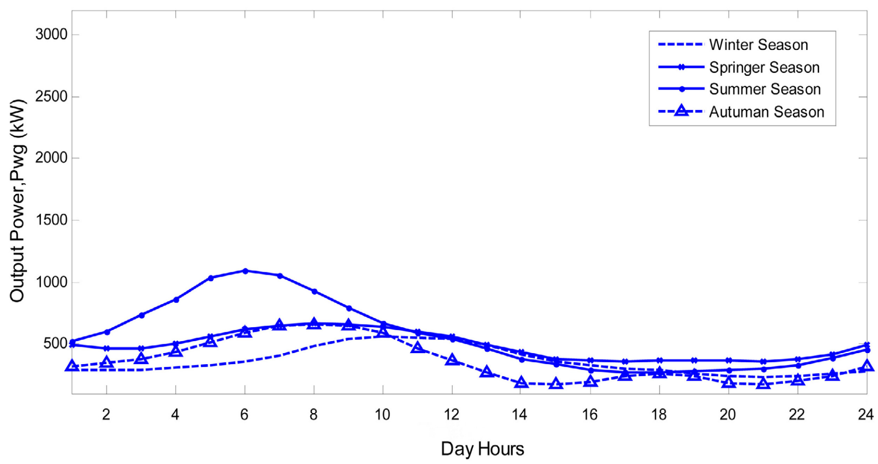

Figure 12. Average daily generation curve of (1500) kW-wind generator mode through different seasons for Hurghada site.

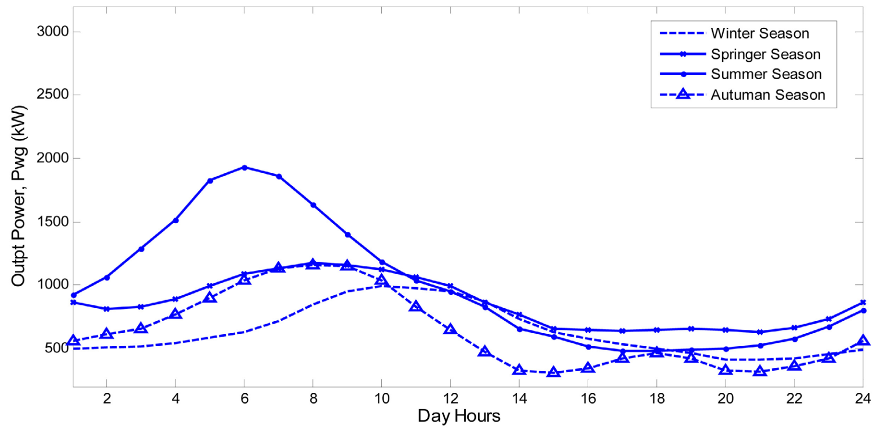

Figure 13. Average daily generation curve of (2000) kW-wind generator mode through different seasons for Hurghada site.

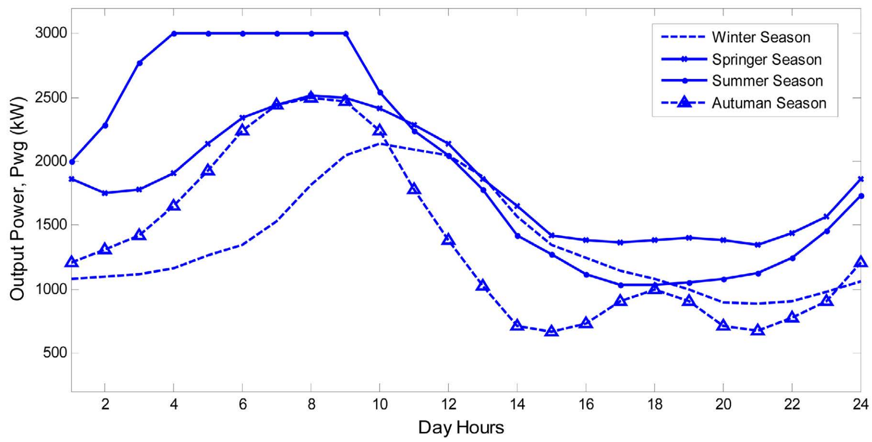

Figure 14. Average daily generation curve of (3000) kW-wind generator mode through different seasons for Hurghada site.

Table 3. A comparison of algorithms to solve PBUCP.

Method	Profit ($)
Parallel BSC-OPL algorithm	1.08623×10^5
BSCA [28]	1.07356×10^5
PNACO [32]	1.05942×10^5
BFWA [33]	1.06850×10^5

- Technical optimization of wind energy generation system installed in Hurghada site.

The technical optimization as illustrated in **Table 4** is carried out using the proposed model to develop the optimal wind generator mode type to supply the study IEEE 10-units test system from a technical point of view.

Table 4 concludes that, the wind generator mode of 3000 kW rate is the most technical one of the studies wind generator modes to be installed at Hurghada site compared with 1500 and 2000 kW-wind generator modes.

Table 4. The technical study of the wind generator modes.

Wind generator mode, kW	1500	2000	3000
Annual energy output, MWh	3865.235	6822.578	14309.055
Swept area, m^2	3848	6793	12,305
The annual generations per unit area	1.00448	1.00435	1.16286

- Economical optimization of wind energy generation system installed in Hurghada site.

The economic optimization is carried out using the proposed model to develop the optimal wind generator mode type to supply the study IEEE 10-units test system from an economic point of view. The capital, annual operation and unit energy costs of the study wind generator modes are determined and taken the following assumption under consideration [21] [23]:

1) The capital cost is \$ 350/1 m^2 of $\mathcal{A}_T$.

2) The operation cost is 1.0 ¢/kWh of $\mathcal{E}_{\mathcal{W}g(a)}$.

3) The life time and interest rate are 20 years and 12%.

The results of **Table 5** concludes that, the wind generator mode of 3000 kW rate is the most economical one of the studies wind generator modes to be installed at Hurghada site compared with 1500 and 2000 kW-wind generator modes.

According to the results of both **Table 4** and **Table 5**, the wind generator mode of 3000 kW rate is the most economical and technical wind generator mode to be installed at Hurghada site.

In this paper, 5% penetration level of wind power generation installed in Hurghada integrated with IEEE10-units test system. The wind farm consists of (35*3000 kW) wind generator modes which are operating in parallel. **Table 6** shows a comparison of the total operation cost in regulated and deregulated systems.

Table 6 concludes that the total operating cost of a deregulated system is lower than that of a regulated system and the total profit of generation company is equal to 1.1080 * 10^5/day.

Figure 15 shows the variation of the total cost with the number of iterations determined by the parallel BSC-OPL algorithm in the regulated and deregulated system during the summer season. **Figure 16** shows the daily generation curve of IEEE 10-units test system integrated with one wind farm without limit in the summer season in a regulated system. Where, **Figure 17**. The daily generation curve of IEEE 10-units with one wind farm using parallel BSC-OPL algorithm without thermal generation units limit at summer season in deregulated system. And also, **Figure 18** and **Figure 19**. Configuration of unit commitment with one wind farm problem without thermal generation limit using parallel BSC-OPL algorithm at summer season in regulated system and deregulated system, respectively.

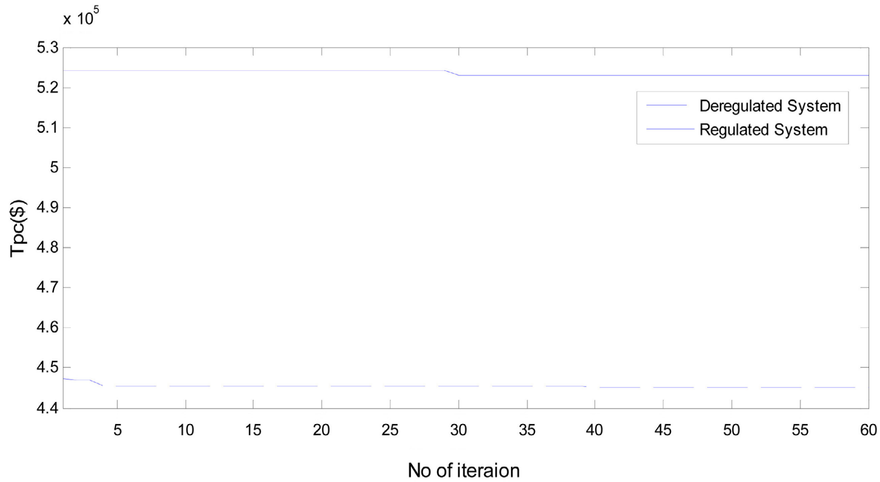

Figure 15. Variation of the total cost of operation determined by the parallel BSC-OPL algorithm with the number of iterations during the summer season in the regulated and deregulated system at the Hurghada site.

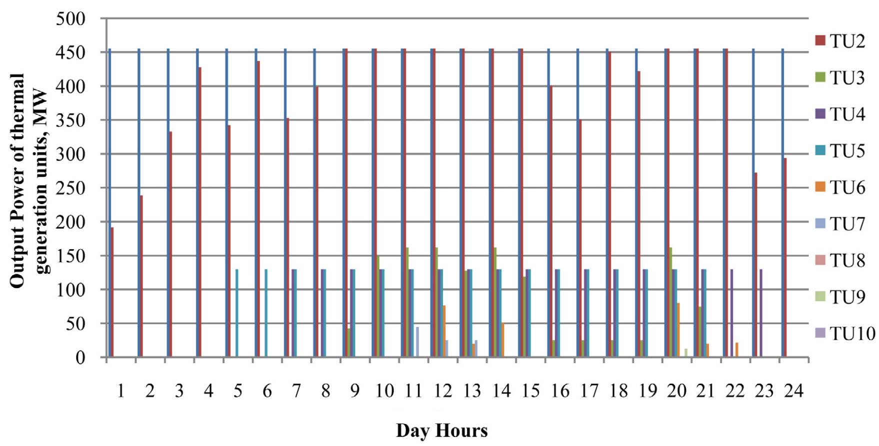

Figure 16. The daily generation curve of IEEE 10-units test system integrated with one wind farm at summer season in regulated system.

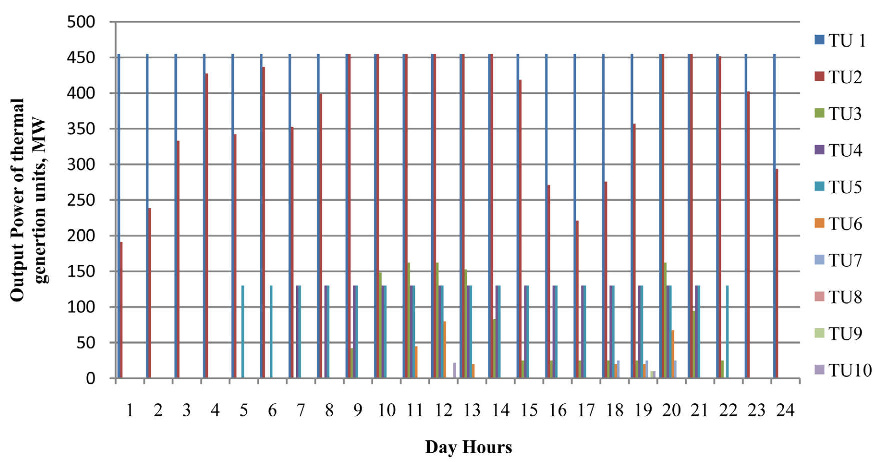

Figure 17. The daily generation curve of IEEE 10-units test system integrated with one wind farm using parallel BSC-OPL algorithm at summer season in deregulated system.

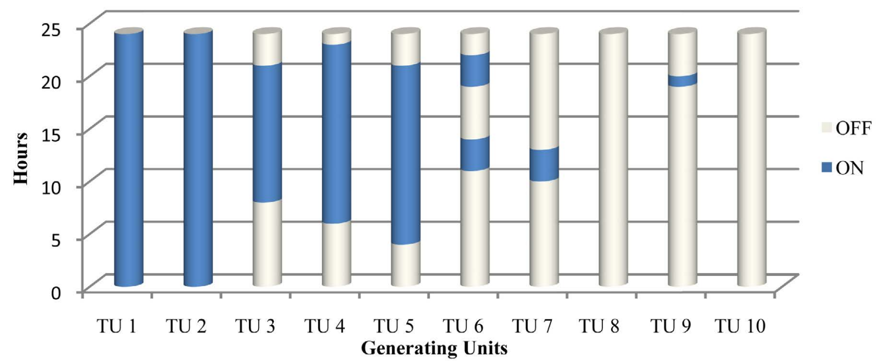

Figure 18. Configuration of unit commitment integrated with one wind farm using parallel BSC-OPL algorithm at summer season in regulated system.

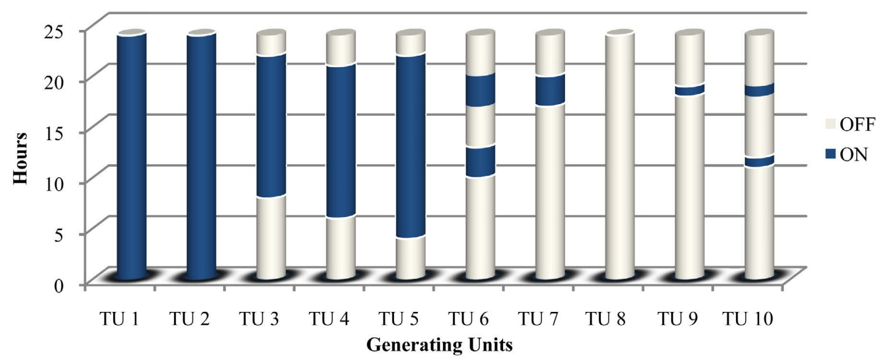

Figure 19. Configuration of unit commitment integrated with one wind farm using parallel BSC-OPL algorithm at summer season in deregulated system.

Table 5. The economy study of the wind generator modes.

Wind generator mode, kW	1500	2000	3000
Capital cost, $	180471.2	2,377,550	4,306,750
Annual operation cost, $	38652.35	68225.78	143050.55
Unit energy cost, ¢/kWh	5.66909	5.66967	5.03286

Table 6. A comparison of total cost per day in the regulated and deregulated system.

Method	Regulated system	Deregulated system
parallel BSC-OPL algorithm	5.2681×10^5 $	4.4318×10^5 $

5. Conclusions

This paper presents a solution of UCP and PBUCP integrated with wind energy generation system by using the proposed parallel BSC–OPL algorithm.

OPL is the first stage of this algorithm which ranks the thermal units according to the average differential rate of fuel cost for the operating unit at its maximum power. This stage shrunk the search space. The BSC is the second stage which determines the optimal solution of the ELD. With the incorporation of these two stages, the search process has been accelerated.

The results of the proposed algorithm have been comprised with the results of the Grey Wolf algorithm and this comparison confirms the efficiency and accuracy of the proposed parallel BSC-OPL algorithm.

The limitation of the thermal generation units has increased the total operation cost of the system.

The Wind generator mode (3000 kW) has been the most economical and technical Wind generator mode to be installed at Hurghada site.

The proposed parallel BSC-OPL algorithm has been applied to IEEE 10-units test system integrated with wind energy generation system consisting of (35 * 3000 kW) at an actual site (Hurghada site in Egypt) to determine the optimal total operation cost in regulated & deregulated system. Also, the optimal profit of the generation company has been determined which leads to obtaining the economical load dispatch.

Although the use of parallel BSC-OPL algorithms to solve the PBUCP is satisfactory, the following suggestions for future work have given rise to a number of research topics in this field:

- Transforming the electricity network utility of Hurghada city into a deregulated system by dividing it into multi-areas to study the profit-based unit commitment problem and the price of a kilowatt hour. Profit-based unit commitment problems will be studied with additional constraints, such as reliability and emissions constraints.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Table A1. Thermal unit data of 10-units 24-hours system.

variable	TU_1	TU_2	TU_3	TU_4	TU_5	TU_6	TU_7	TU_8	TU_9	TU_{10}
$P_{n,\max}$	455	455	130	130	162	80	85	55	55	55
$P_{n,\min}$	150	150.00	20	20	25	20	25	10	10	10
α_n (\$/h)	1000.00	970	700	680	450	370	480	660	665	670
β_n (\$/MWh)	16.19	17.26	16.60	16.50	19.7	22.26	27.74	25.92	27.27	27.79
γ_n (\$/MWh^2)	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
$\mathcal{T}_n^{up}$ (h)	8	8	5	5	6	3	3	1	1	1
$\mathcal{T}_{n,down}$	8	8	5	5	6	3	3	1	1	1
$\mathcal{SH}_n$ (\$)	4500	5000	550	560	900	170	260	30	30	30
$\mathcal{SC}_n$ (\$)	9000	10,000	1100	1120	1800	340	520	60	60	60
$\mathcal{T}_n^{cold}$ (h)	5	5	4	4	4	2	0	0	0	0
Initial status (h)	8.0	8	−5	−5	−6	−3	−3	−1	−1	−1

Table A2. The PLD for 24-hour.

Hour	1	2	3	4	5	6	7	8	9	10	11	12
PLD	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500
Hour	13	14	15	16	17	18	19	20	21	22	23	24
PLD	1400	1300	1200	1050	1000	1100	1200	1460	1300	1100	900	800