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OPTIMAL THERMAL GENERATING UNIT COMMITMENT WITH WIND POWER IMPACT: A PSO-IIW PROCEDURE

H. Shayeghi [1] H. Gholamalitabar Firoozjaee [1] A. Ghasemi [2] O. Abedinia [2] R. Bazyar [3]

1. Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran, hshayeghi@gmail.com
2. Young Researcher Club, Ardabil Branch, Islamic Azad University, Ardabil, Iran, oveis.abedinia@gmail.com
3. East Azarbaijan Power Generation Management Company, Ardabil, Iran, bazyar.reza@yahoo.com

Abstract- The wind energy is expected to play a significant role in remedying the many shortcomings in today's modern energy electricity market. In the other hand, wind power becomes a far bigger issue when its total contribution in the renewable power system increases. An improved Standard Particle Swarm Optimization (SPSO) which called Particle Swarm Optimization with Improved Inertia Wight (PSO-IIW) is proposed to solve the Unit Commitment (UC) problem between thermal generating units with wind impact an electricity market to minimize total cost. To achieved a real system considered with various generator and wind constraints in power systems. To demonstrate the effectiveness and robustness of the proposed algorithm a system with ten thermal and wind units with various condition is simulated. The results and numerical experiments are compared with SPSO, Genetic Algorithm (GA) and λ-iteration to understand the wind generator capacity in production cost analysis and to provide valuable information for both operational and planning problems.

Keywords: PSO-IIW, Wind Energy, UC Problem, Electricity Market.

I. INTRODUCTION

Recently, the problem of low cost of energy generation and its environmental advantages, using wind energy in electric power generation, has been seemed useful. The drastic changes in environment and climate can be avoided by replacing fossil energy sources with clean and fuel free energy generation [1]. The growing concern for environment has asked for rapid developments in wind power generation technology. On the other hand because of variability and uncertainty of this energy, using it has made some challenges to power system operators. In order to adjust the unforeseeable nature of the wind power, planned productions and uses in electricity market must be improved during the real operation of the power system [2, 3].

Actually, with the increased penetration of the wind energy, there will be huge fluctuation in the power generation. Therefore storage devices such as pumped storage are necessary. The pumped storage is used to level the mismatch between power generation and demand. They store the excess generation from wind farms and also the excess generation by the base load generation plants during off-peak periods for later use [4]. This will enable efficient utilization of the base-load generation units and to smooth the peak loads. The pumped storage can also be used to provide reserve during off-peak period so that no other unit is committed just for providing the reserve [5].

In other hand, decrease of production of the air pollutant gases is under consideration as behavioral patterns in countries industries are considered. So the level of produced gases by plants must be minimized in operation planning of them. Also, Unit Commitment (UC) and Energy Dispatch (ED) operations are of great importance because of their strong economic impact and increasing emissions concerns. Commitment of the wind plants in power generation increases the importance of considering the generating pollution of thermal units [5]. Because on one hand these wits are not producers of the air pollutant gases, but on the other hand the generating pollution curve of the thermal units is in a way that by high decrease in their generating power level, their generated pollution level increases. By increasing the penetration of wind power generation and providing the load by it, power level of the thermal units decreases [6].

In recent years, several UC studies analyzing the impact of increasing adoption levels of wind power have been performed. Where, dynamic programming [6], branch-and-bound [7], Lagrangian Relaxation (LR) approach [9], Genetic Algorithm (GA) [10], and Evolutionary Programming (EP) [11], could be used to solve the extended unit commitment problem. In [11], a security-constrained stochastic UC formulation that accounts for wind power volatility is presented together with an efficient Benders decomposition solution technique. But, the issue of constructing probability distributions for the wind power is not addressed. In [9], a detailed closed-loop stochastic UC formulation is reported. The authors analyze the impact of the frequency of recommitment on the production, startup, and shutdown costs.

They find that increasing the recommitment frequency can reduce costs and increase the reliability of the system. However, the authors do not present details on the wind power forecast model and uncertainty information used to support their conclusions. In [7, 9], Artificial Neural Network (ANN) models are used to compute forecasts and confidence intervals for the total aggregated power for a set of distributed wind generators. Such approaches can thus result in inaccurate medium and long term forecasts and over- or under-estimated uncertainty levels [6, 8], which in turn affect the expected cost and robustness of the UC solution.

This paper presents, a PSO-IIW method incorporated with a simplified dispatch method is developed to solve the problem of combining unit commitment of the generating units while minimizing the cost. Actually, the fundamental idea of the proposed technique is based on PSO-IIW. Application results of the proposed algorithm to several test systems are presented to illustrate its effectiveness. The results are demonstrated that the proposed technique is superior to the other compared methods.

II. PROBLEM FORMULATION

Wind energy conversion is the fastest-growing source of new electric generation in the world and it is expected to remain so for some time. Its long lifespan, emission-free operation and low cost have made it more attractive compared to the other sources [12]. One of the most important functions of modern energy management system is solving the wind-thermal scheduling problem, which determines the optimal real power settings of generating units for a specific period of operation and in return satisfying the system load demand with minimizing the total fuel cost subjected to the operating constraints of a power system [12]. In this paper considered wind power energy by the public utility. The objective of optimal wind-thermal generating unit commitment problem is to simultaneously minimize the generation cost rate and meet the load demand of a power system over some appropriate period while achieving various constraints depending on assumptions and practical implications [12]. The constrained UC optimization problem can be expressed as follows:

$$F_T = \sum_{t=1}^{T}\sum_{i=1}^{NT} F_i(P_i(t)) \tag{1}$$

The problem constraints are:

(1) Power balance: This constraint is based on the principle of equilibrium between total system generation and total system loads (PD) and losses (PL),

$$\sum_{i=1}^{NT} U_i(t)P_i(t) + P_{wt}(t) = P_L(t) \tag{2}$$

b) System up/down spinning reserve requirements:

$$\sum_{i=1}^{NT} U_i(t)US_i(t) \ge USR_B + ASR_1(P_{WT}(t)) \tag{3}$$

$$\sum_{i=1}^{NT} U_i(t)DS_i(t) \ge ASR_2(P_{WT}(t)) \tag{4}$$

c) Minimum/maximum thermal plant output constraints:

$$P_L(t) - P_{WT}(t) = ASR_2(P_{WT}(t)) + \sum_{i=1}^{NT} U_i(t)P_i^{\min}(t) \tag{5}$$

$$\sum_{i=1}^{NT} U_i(t)P_i^{\max}(t) + P_{WT}(t) \ge P_L(t) + USR_B + ASR_1(P_{WT}(t)) \tag{6}$$

2) Thermal Generator Constraints:

a) Unit's maximum up/down reserve contribution constraints:

$$US_i^{\max} = d\% \times P_{i,r}^{\max} \tag{7}$$

$$DS_i = d\% \times P_{i,r}^{\max} \tag{8}$$

b) Unit's up/down spinning reserve contribution constraints:

$$US_i(t) = \min\{\, US_i^{\max},\ P_{i,r}^{\max} - P_{i,r}(t)\} \tag{9}$$

$$DS_i(t) = \min\{\, DS_i^{\max},\ P_i(t) - P_{i,r}^{\min}\} \tag{10}$$

c) Unit's ramping up/down capacity constraints:

$$UR_i(t) = \min\{\, UR_i^{\max},\ P_{i,r}^{\max} - P_i(t)\} \tag{11}$$

$$DR_i(t) = \min\{\, DR_i^{\max},\ P_i^{\max} - P_{i,r}^{\min}\} \tag{12}$$

d) Unit generation limits:

$$P_i^{\min}(t)U_i(t) \le P_i(t) \le P_i^{\max}(t)U_i(t) \tag{13}$$

$$P_i^{\max}(t) = \begin{Bmatrix} \min\{P_{i,r}^{\max}, P_i(t-1)+UR_i^{\max}\} \\ \min\{P_{i,r}^{\max}, P_i(t-1)+SR_i\} \end{Bmatrix} \begin{matrix} \text{if } U_i(t)=U_i(t-1)=1 \\ \\ \text{if } U_i(t)=1, U_i(t-1)=0 \end{matrix}$$

$$P_i^{\min}(t) = \begin{Bmatrix} \min\{UR_i^{\max}, P_i(t-1)-DR_i^{\max}\} \\ P_{i,r}^{\min}\ if\quad U_i(t)=1, U_i(t-1)=0 \end{Bmatrix} \tag{14}$$

$$\text{if}\quad U_i(t) = U_i(t-1) = 1$$

e) Minimum up/down time constraints:

$$\left[t_{ON,i}(t-1) - T_{ON,i}\right].\left[U_i(t-1)U_i(t)\right] \ge 0 \tag{15}$$

$$\left[t_{OFF,i}(t-1) - T_{OFF,i}\right].\left[U_i(t-1)U_i(t)\right] \ge 0 \tag{16}$$

3) Wind Generator Constraints:

a) Wind generation fluctuation constraints:

$$P_{WT}(t) - P_{WT}(t-1) \le TDR(t), \quad \text{if} \quad P_{WT}(t-1) \le P_{WT}(t) \tag{17}$$

$$P_{WT}(t-1) - P_{WT}(t) \le TDR(t), \quad \text{if} \quad P_{WT}(t-1) \ge P_{WT}(t) \tag{18}$$

b) Wind power curve constraints:

$$P_{wi}^*(t) = \begin{cases} 0 & V(t) \le V_{Ij} \ \text{ or } \ V(t) > V_{Oj} \\ \varphi_j(v(t)) & V_{Ij} \le V(t) \le V_{Rj} \\ P_{wj}^{\max} & V_{Rj} \le V(t) \le V_{Oj} \end{cases} \tag{19}$$

c) Total available wind generation:

$$P_{WT}^*(t) = \sum_{j=1}^{NW} P_{wi}^*(t) \tag{20}$$

d) Total actual wind generation limit:

$$0 \le P_{WT}(t) \le P_{WT}^* \tag{21}$$

III. PSO-IIW PROCEDURE

A. Standard PSO Algorithm

The standard of the Particle Swarm Optimization (PSO) are best describe as sociologically inspired, since the original algorithm was based on the sociological behavior associated with bird flocking [15,16]. PSO is simple in concept, few in parameters, and easy in implementation, besides it has an excellent optimization performance. At first, PSO was introduced for continuous search spaces and because of the mentioned features; it has been widely used to many optimization problems soon after its introduction [17].

To explain how PSO algorithm works, an optimization problem which requires optimization of N variables simultaneously is considered here. PSO is initialized with a population of solutions, called “particles”. At first, a random position and velocity is assigned to each particle. The position of each particle corresponds to a possible solution for the optimization problem. A fitness number is assigned to each particle which shows how good its position is. During the optimization process, each particle moves through the *N*-dimensional search space with a velocity that is dynamically adjusted according to its own and its companion’s previous behavior. Updating the particle velocity is based on three terms, namely the “social,” the “cognitive,” and the “inertia” terms. The “social” part is the term guiding the particle to the best position achieved by the whole swarm of particles so far (*gbest*), the “cognitive” part guides it to the best position achieved by itself so far (*pbest*), and the “inertia” part is the memory of its previous velocity ($\omega.v_n$). The following formulae demonstrate the updating process of a particle position (x_n) and its velocity (v_n) in the nth dimension in an *N*-dimensional optimization space [18]:

$$v_i^{k+1} = wv_i^k + c_1R_1\left(pbest_i^k - x_i^k\right) + c_2R_2\left(gbest^k - x_i^k\right) \quad (22)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (23)$$

In Equation (16), R_1 and R_2 are random numbers uniformly distributed between 0 and 1. c_1 and c_2 are acceleration constants and ω is the inertia weight. These three parameters determine the tendency of the particles to the related terms. Moreover, another parameter is used to limit the maximum velocity of a particle (V_{max}). All these parameters directly affect the optimization behavior; for example, the inertia weight controls the exploration ability of the process while the acceleration constants and maximum velocity are parameters for controlling the convergence rate [15, 16]. The iterative procedure of updating the velocities and positions of particles continues until the best position achieved by the whole swarm of particles (*gbest*) does not change over several iteration. Figure 1 shown this process obviously.

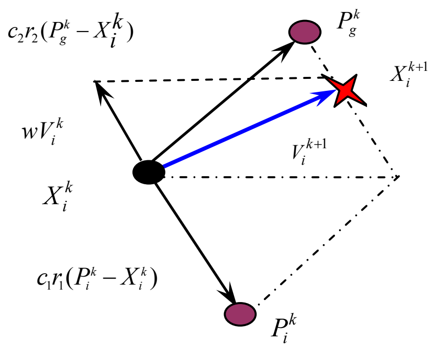

Figure 1. Velocity and location of particle updating process

B. PSO-IIW

The main disadvantage of using this PSO method is that once the inertia weight is decreased, the swarm is not able to recover from its exploration mode and loses its ability to search in new areas. Therefore, the Particle Swarm Optimization with Improved Inertia Weight (PSO-IIW) is a new evolutionary algorithm implemented by means of the Direct Search Method (DSM) to meet the requirements of a real-valued particle swarm optimization [19, 20]. The main concept of PSO-IIW is similar to CPSO in which the Equations (22) and (23) are used. However, for PSO-IIW the inertia weight ω is modified by the constriction factor *Z*. This inertia weight (ω) plays the role of balancing the global and local exploration abilities. Here, for PSO-IIW the inertia weight (ω) is modified. The proposed weighting function is defined as follows:

$$\begin{cases} \omega_{qi}^k = \omega_{\max} - \dfrac{(\omega_{\max} - \omega_{\min})Z_{iter,qi}^k}{Z}, & \text{if} \quad v_{qi}^k \times (x_{i,gbest}^k - x_{qi}^k) > 0 \\ \omega_{qi}^k = \omega_{qi}^{k-1} & \text{,if} \quad v_{qi}^k \times (x_{i,gbest}^k - x_{qi}^k) < 0 \end{cases} \quad (24)$$

$$q = 1, 2, \ldots, Q; \quad i = 1, 2, \ldots, N$$

where, $\omega_{\max}$ and $\omega_{\min}$ are maximum and minimum value of weighting factor, respectively. The $\omega^k{}_{qi}$ is element inertia weight *i* of particle *q* in iteration *k*. Also, the parameter *Z* is replaced with $iter_{\max}$ in original PSO as an important factor to control and balanced mechanism between the global and local exploration abilities. For acquire parameter *Z* value, thus requiring less runs on average to find a sufficiently optimal solution. Also, for PSO-IIW the velocity update equation is modified by the constriction factor C. therefore, the velocity of each agent can be modified by the following equation:

$$v_i^{k+1} = C\{wv_i^k + c_1R_1\left(pbest_i^k - x_i^k\right) + \\ + c_2R_2\left(gbest^k - x_i^k\right)\} \quad (25)$$

$$C = \frac{2}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|}, \quad \text{where} \quad 4.1 \le \phi \le 4.2 \quad (26)$$

where, R_1 and R_2 are two random functions they are distributed with uniform probability in the interval [0 1].

C. Benchmark

At first, the proposed technique is applied in one standard benchmark. For more information about PSO-IIW algorithm the rastrigin function which is used in this paper, is presented as:

$$f(x) = 20 + \sum_{i=1}^{n}(x_i^2 - 10\cos(2\pi x_i)) \quad (27)$$

$$-3 \le x_1 \le 12.1, \; 4.1 \le x_2 \le 12.8$$

Also Figure 2 shows the output of the software for objective function’s shape. There is no doubt that PSO-IIW algorithm is one of the heuristic algorithms. Also this algorithm should be run several times to find the best answer for objective function. Table 1 presents the average results over many runs. Figure 3 also shows the PSO-IIW's convergence curve.

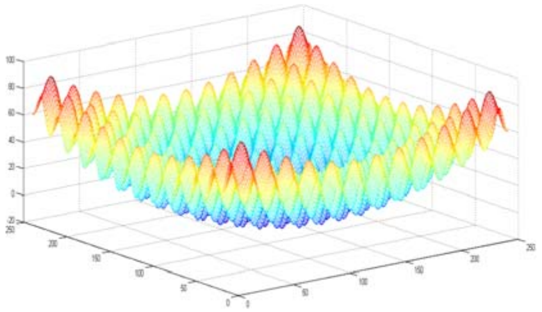

Figure 2. 3-D display of rastrigin function

Table 1. The average results over many runs of PSO-IIW

Run	Max	Ave	Min	X_1	X_2
1	28.2811	20.415	19.8316	0.9931	4.1025
2	28.2813	20.417	19.8317	0.9930	4.1023
3	28.2824	20.418	19.8316	0.9931	4.1025
4	28.2878	20.416	19.8316	0.9931	4.1025
5	28.2809	20.414	19.8317	0.9931	4.1025
6	28.2799	20.416	19.8316	0.9931	4.1025
7	28.2834	20.415	19.8318	0.9930	4.1023
8	28.2865	20.413	19.8317	0.9932	4.1025
9	28.2853	20.411	19.8316	0.9931	4.1025
10	28.2832	20.419	19.8316	0.9931	4.1025
SD	0.0025	0.0022	0.0001	0.0001	0.0001

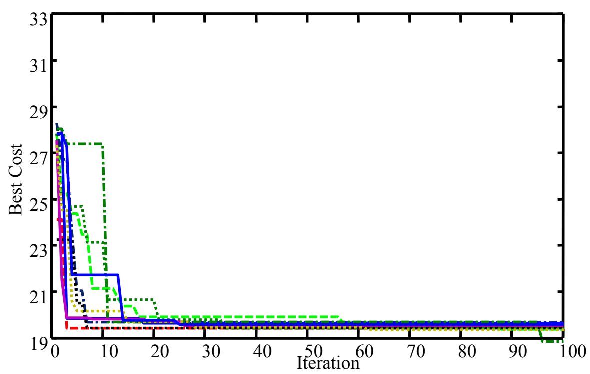

Figure 3. PSO-IIW's convergence curve in many runs

IV. THE PSO-IIW BASED UC PROBLEM

When any optimization process is applied to the UC problem some constraints are considered [21, 22]. In this paper some different constraints are considered. Among them the equality constraint is summation of all the generating power must be equal to the load demand and the inequality constraint is the powers generated must be within the limit of maximum and minimum active power of each unit. The procedure of PSO-IIW algorithm for the UC problem solution can be described as follows:

- Step 1: Particle initialization: The individuals of the population are randomly initialized according to the limit of each unit including individual dimensions. The velocities of the different particles are also randomly generated keeping the velocity within the maximum and minimum value of the velocities [21]. These initial individuals must be feasible candidate solutions that satisfy the practical operation constraints. The ith swarm for n generating units is represented as:

$$P_i = [P_{i1}, P_{i2}, ..., P_{in}] \tag{28}$$

- Step 2: Satisfy the constrains: Each set of solution in the space should satisfy the equality constraints .So equality constraints are checked. If any combination doesn't satisfy the constraints then they are set according to the power balance equation.

$$\sum_{i=1}^{NT} U_i(t)P_i(t) + P_{wt}(t) = P_L(t) \tag{29}$$

- Step 3: Evaluation of fitness: The evaluation function of each individual P_{gi}, is calculated in the population using the evaluation function F_T .Here F_T is:

$$F_T = \sum_{t=1}^{T}\sum_{i=1}^{NT} F_i(P_i(t)) \tag{30}$$

- Step 4: Greedy selection mechanism: Each pbest values are compared with the other pbest values in the population. The best evaluation value among the p-bests is denoted as gbest.

- Step 5: Update: The member velocity v of each individual P_g is modified according to the velocity update equation.

$$v_i^{k+1} = C + \{wv_i^k + c_1R_1(pbest_i^k - x_i^k) + \\ +c_2R_2(gbest^k - x_i^k)\} \tag{31}$$

- Step 6: Domain Velocity: The velocity components constraint occurring in the limits from the following conditions are checked:

$$V^d{}_{\min} = -0.5P_{\min} \tag{32}$$

$$V^d{}_{\max} = -0.5P_{maz} \tag{33}$$

- Step 7: Update position: The position of each individual P_g is modified according to the position update equation as the following:

$$P^{u+1} = P^u + V_{id}{}^{(u+1)} \tag{34}$$

- Step 8: Replace: If the evaluation value of each individual is better than previous *pbest*, the current value is set to be pbest. If the best pbest is better than *gbest*, the value is set to be gbest.

- Step 9: Check criteria: If the number of iterations reaches the maximum, then go to step 10. Otherwise, go to step 2.

- Step 10: Display: The individual that generates the latest gbest is the optimal generation power of each unit with the minimum total generation cost.

V. RESULTS AND DISCUSSIONS

In order to illustrate the efficiency of the proposed PSO-IIW algorithm for the solution of the proposed problems, three power systems, including several test systems. All the computations are performed on a Not Book (NB) intel core 2 Duo processor P8700 (2.53 GHZ), RAM 4 GB and several computer programs were developed in MATLAB 2009a. In order to acquire better performance, the control parameters of the proposed PSO-IIW, PSO and GA algorithms is given in Table 2.

Table 2. PSO-IIW, SPSO and GA control parameters for optimization

PSO-IIW		SPSO		GA	
c_{1f}	0.2	c_1	2.1	Population type	Double vector
c_{1i}	2.5	c_2	2.1	population	80
c_{2f}	2.5	$\omega_{\min}$	0.4	Iteration	200
c_{2i}	0.2	$\omega_{\max}$	0.9	Selection	Tournament
φ	4.1	Population	60	Mutation	Uniform
$\omega_{\min}$	0.4	Iteration	200	Stopping criteria	Generations
$\omega_{\max}$	0.9			Initial penalty	1.8
Population	40			Crossover fraction	0.85
Iteration	200			Elite count	2.0
Z	100				

A. Case I: 10-Unit Thermal System without Wind Power

In this test case contains 10 generating units without wind power effect. The required system unit data and the generation requirements for each stage are given in [12]. The determined schedule using GA, SPSO, PSO-IIW technique is given in Table 3. The optimal results using the proposed methods in comparison than the other heuristic methods are shown in Table 4 that satisfies the generator constraints. It can be apparent from this Table that the proposed PSO-IIW technique provided superior solutions compared with other reported evolutionary algorithm methods. Figure 4 shows the minimum fitness functions evaluating process.

Table 3. The determined commitment schedule

Units	Hour (1→24)
	PSO-IIW
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1
5	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
6	1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	SPSO
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1
5	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
6	1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	GA
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1
5	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
6	1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

Table 4. The computing time and the total cost for test case I

Method	Time (sec)	Min Cost ($)
λ - iteration	10.93	78907
FDP	NA	78895.5
GA	13.92	78896.14
SPSO	8.827	78804.65
PSO-IIW	8.263	78724.39

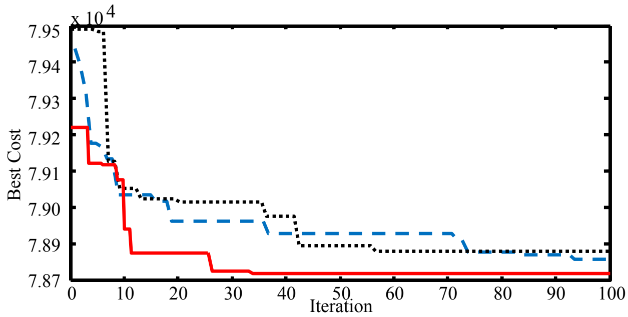

Figure 4. Fitness convergence, dashed (PSO-TVIW)

B. Case II: Test for 10-Unit Thermal System with an Equivalent Wind Generator

In this test, the performance of the proposed PSO-IIW based UC under practical conditions is verified by applying an equivalent wind generator. For achieved better discussion and analyze of the numerical results considered system with small capacitor. The accessible wind power generation considered 400 MW for all hours. Actually, the adjustments of the power output are instantaneous that it is considered in the studied cases. Accordingly, generators are constrained because of ramp rate limits where, generation may increase or decrease with corresponding upper and downward ramp rate limits. The generator ramp rate and startup ramp rate constraints are set at 60% of its rated capacity. Also, the system up spinning reserve requirement is assumed to be 300 MW for all time periods. The thermal power units is more than 20% of its rated capacity (d% = 20%). The best cost solution for different methods with constraint satisfaction is shown in Table 5.

Table 5. The computing time and the total cost for test case II

Method	Time (sec)	Min Cost ($)
FDP [12]	84.81	58233
HDP [12]	30.87	58233
HDP* [12]	10.71	58233
GA	47.82	58232.87
SPSO	9.716	58232.19
PSO-IIW	9.134	58231.87

To illustrate the accuracies of these methods, a maximum number of iteration cycles are considered as a stopping condition. Each algorithm is run for ten trials and the best fitness value, Standard Deviation (SD), the least iteration and elapsed time achieved by each algorithm are considered as criteria of the strength and computational effort of the method. The results using the SPSO, PSO-IIW and GA algorithms based on the objective function as given in Equation (1) for optimal setting of the UC problem are listed in Table 6. It can be seen that the best SD and the best fitness value in 6 times are achieved by the PSO-IIW than the other methods. Also, it has fewer iterations and less computational time to reach a predefined threshold in comparison to other algorithms. The best fitness achieved by the PSO-IIW is 58231.87 which equals to the lowest among the three algorithms.

Table 6. Different methods results for 10 trials

Run	GA				
	Min	Max	Mean	Time	Iter.
1	58232.87	58235.43	58233.86	47.82	97
2	58233.54	58237.67	58233.64	47.85	95
3	58232.99	58235.49	58234.82	47.84	98
4	58233.23	58236.74	58233.89	47.83	89
5	58232.83	58235.92	58234.77	47.85	76
6	58233.07	58238.45	58233.87	47.82	96
7	58232.56	58235.44	58233.10	47.83	90
8	58232.76	58238.23	58235.34	47.82	93
9	58233.25	58236.78	58234.55	47.84	87
10	58232.80	58235.48	58233.76	47.84	88
SD	0.2735	1.1369	0.6445	0.0111	6.2
Run	SPSO				
	Min	Max	Mean	Time	Iter.
1	58232.19	58235.32	58233.45	9.716	57
2	58232.34	58235.39	58233.56	9.717	64
3	58232.24	58235.38	58233.78	9.716	54
4	58232.31	58234.67	58233.89	9.718	60
5	58232.27	58235.39	58233.90	9.715	53
6	58232.33	58234.38	58233.12	9.716	49
7	58232.30	58235.56	58233.03	9.716	65
8	58232.42	58235.78	58233.65	9.717	63
9	58232.26	58235.29	58233.33	9.716	58
10	58232.37	58235.56	58233.75	9.717	84
SD	0.0633	0.4030	0.2923	0.0008	9.1
Run	PSO-IIW				
	Min	Max	Mean	Time	Iter.
1	58231.87	58234.76	58232.12	9.134	24
2	58231.88	58234.78	58232.23	9.135	26
3	58231.87	58234.89	58232.18	9.136	29
4	58231.87	58234.56	58232.20	9.134	30
5	58231.89	58234.35	58232.22	9.133	26
6	58231.90	58234.28	58232.25	9.135	23
7	58231.88	58234.55	58232.21	9.134	28
8	58231.87	58234.39	58232.19	9.136	26
9	58231.89	58234.98	58232.18	9.135	29
10	58231.87	58234.74	58232.23	9.134	26
SD	0.0104	0.2261	0.0348	0.0009	2.1

Furthermore, to evaluate the efficacy and robustness of the proposed optimization technique numerous operating conditions and the system configurations, simultaneously is are considered. The multiple operation conditions are given in Table 7. The scenario I and III give a comparison of results considering the wind generation curtailment or not.

Table 7. Comparison of results for five different cases in test case II

Scenario	I	II	III	IV	V
$P^*_{WT}(t)$ MW	0	400	400	400	400
USR_B MW	300	300	300	300	300
ASR_1	---	LM	LM	LM	SM
ASR_2	---	---	---	LM	LM
WGC	---	without	with	with	with
HDP*	78911	58134	57955	58233	58790
GA	78913	58133	57955	58233	58791
SPSO	78910	58133	57954	58233	58790
PSO-IIW	78908	58130	57952	58232	58788

WGC: Wind Generation Curtailment.
LM (Linear Model): γ%=0.2.
SM (Second-order Model): α%=0.2, β%=10^{-4}.

It can be seen according to Table 8 that the wind generator is out in power system at low system load times (hours 11-17). Also, it shows the impact of introducing power system down spinning reserve requirement into the generation scheduling problem.

The determined schedule using GA, SPSO, PSO-IIW technique with contain the system down spinning reserve requirement or not are given in Table 9.

Table 8. Comparison of results considering the wind generation curtailment or not

Scenario	Hour	1→10	11→14	15→16	17	18→24
II	$P^*_{WT}(t)$	400	400	400	400	400
III	MW	400	395	385	395	400

Table 9. The determined commitment schedule

Units	Hour (1→24)
	PSO-IIW
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
5	1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
6	1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	SPSO
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
5	1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1
6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	GA
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
5	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
6	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
7	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
8	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

VI. CONCLUSIONS

The continuous increasing of the global energy demand is a reality. It is well-known that conventional sources of energy are running out rapidly and they cannot cover this tremendous demand. Renewable energies such as hydro, wind, solar, biomass, and biofuels have been under an intensive development since 1970s; and nowadays, they have become efficient, reliable and competitive sources of energy, supplemental to conventional sources.

Renewable energies are seen as one of the solutions that will help meeting, on the one hand, the increasing global energy demand; and on the other hand, reducing the greenhouse gases emissions.

A Particle Swarm Optimization with Improved Inertia Wight (PSO-IIW) method is proposed to find fesible solution in UC problem with considered wind power energy in this paper. It has a strong ability to successful control the local search and convergence to the global optimum solution.

The problem of find best answer is formulated as an optimization problem according to the time domain-based objective function for a wide range of operating conditions and is solved by the PSO-IIW technique which is simple, robust and capable to solve difficult combinatorial optimization problems. The results obtained for three test systems were always comparable or better that the earlier best reported results. From these comparative studies, it is evident that the PSo-IIW can be effectively used for the solution of UC problems in the real world power systems.

NOMENCLATURES

F_T: Total operation cost over the scheduling horizon.
i: Index for thermal units.
j: Index for wind units.
N_T: Number of thermal units in the system.
N_W: Number of wind units in the system.
$P_i(t)$: Generation of thermal unit i at hour t.
$P_{i,r}^{\max}$: Upper generation limit of thermal unit i.
$P_i(t)^{\max}$: Maximum generation of thermal unit i at hour t.
$P_{i,r}^{\min}$: Lower generation limit of thermal unit i.
$P_i(t)^{\min}$: Minimum generation of thermal unit i at hour t.
$P_L(t)$: System load demand at hour t.
ASR_1: Additional up reserve requirement considering wind power generation.
ASR_2: Additional down reserve requirement considering wind power generation.
C_n: Number of states saved at each hour in the HDP algorithm.
$d\%$: Percentage of maximum unit capacity.
$DR_i^{\max}$: Maximum ramp-down rate for thermal unit i.
$DS_i^{\max}$: Maximum down reserve contribution of thermal unit i.
$DS_i(t)$: Down reserve contribution of thermal unit i at hour t.
$P_{Wj}^{\max}$: Upper generation limit of wind unit j.
$P_{Wj}(t)$: Actual generation of wind unit j at hour t.
$P^*_{Wj}(t)$: Available generation of wind unit j at hour t.
$P_{WT}(t)$: Total actual wind generation at hour t.
$P^*_{WT}(t)$: Total available wind generation at hour t.
$r\%$: Coefficient of additional up (or down) reserve requirement (linear model).
SR_i: Startup ramp rate limit of thermal unit i.
T: Number of time intervals (hours).
$TDR(t)$: System ramping down capacity at hour t.
$t_i(t)^{OFF}$: Time period that thermal unit i had been continuously down till period t.
T_i^{OFF}: Minimum down time of thermal unit i.
T_i^{ON}: Minimum up time of thermal unit i.
t^{ON}, $i(t)$: Time period that thermal unit i had been continuously up till period t.
$TUR(t)$: System ramping up capacity at hour t.
$U_i(t)$: Scheduled state of thermal unit i for hour t (1: unit i is up, 0: unit i is down).
$UR_i^{\max}$: Maximum ramp-up rate for thermal unit i.
$US_i(t)$: Up reserve contribution of thermal unit i at hour t.
$US_i^{\max}$: Maximum up reserve contribution of thermal unit i.
$USRB$: System up spinning reserve requirement not considering wind power generation.

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BIOGRAPHIES

Hossein Shayeghi received the B.Sc. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is an Associate Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored and co-authored of five books in Electrical Engineering area all in Farsi, two book chapters in international publishers and more than 180 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of three international journals. He has served on several other committees and panels in governmental, industrial, and technical conferences. He was selected as distinguished researcher of the University of Mohaghegh Ardabili several times. In 2007 and 2010 he was also elected as distinguished researcher in engineering field in Ardabil province of Iran. Also, he is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and IEEE. Currently, he is head of Ardabil Technology Incubation Center (ATIC) at University of Mohaghegh Ardabili since 2008.

Hossein Gholamalitabar Firoozjaee was born in Babol, Mazandaran, Iran, in 1988. He received the B.Sc. degree in Electrical Engineering from the University of Nooshirvani, Babol, Mazandaran, Iran, in 2010. He is currently the M.Sc. student in Electrical Engineering in University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in power market, renewable energy and optimization with artificial algorithms.

Ali Ghasemi was born in Babol, Mazandaran, Iran on 28 September 1986. He received the B.Sc. and M.Sc. (Honors with first class) degrees in Electrical Engineering from Isfahan University of Technology, Isfahan, Iran in 2009 and Technical Engineering Department of the University of Mohaghegh Ardabili, Ardabil, Iran in 2011. His areas of interest in research are power system control and operation, adaptive and robust control of power systems, operation and planning and power system restructuring and applications of heuristic techniques in power systems. He has authored a book in Electrical Engineering area in Farsi, and more than 50 papers in reputable international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of four international journals.

Oveis Abedinia received the B.Sc. and M.Sc. degrees in Electrical Engineering from Ardabil Branch, Islamic Azad University, Ardabil, Iran and Science and Technology Research Branch, Tehran, Iran in 2005 and 2009, respectively. Currently, he is a Ph.D. student in Electrical Engineering Department, Semnan University, Semnan, Iran. His areas of interest in research are application of artificial intelligence to power system and control design, load and price forecasting, distribution generation, restructuring in power systems, congestion management and optimization.

Reza Bazyar was born in Tabriz, Iran in 1984. He received the B.Sc. degree in Electrical Engineering from Azarbaijan Higher Education and Research Complex, Tabriz, Iran, in 2008 and the M.Sc. degree in Electrical Engineering from Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran, in 2011. He is currently an engineer of the East Azarbaijan Power Generation Management Company, Tabriz, Iran. His research interests include economic dispatch, O&M gas power plant, hybrid energy system, Power system control and operation.