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Advanced three-stage pseudo-inspired weight-improved crazy particle swarm optimization for unit commitment problem

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ABSTRACT

This paper proposes an advanced three-stage approach to solve the unit commitment problem. The proposed approach utilizes three different stages to get the optimum solution. In the first stage, a primitive structure of all units is obtained on the basis of predefined priority. In the second stage, a weight-improved crazy particle swarm optimization considering a pseudo-inspired algorithm has been proposed for economic scheduling of operating units. Finally, in the third stage, extra reserve and total operating cost are minimized using solution restructuring process. In addition, problem formulation includes multi-fuel options, prohibited operating zones and nonlinearities like valve point loading effects. The effectiveness of proposed approach is tested on various systems including IEEE 118-bus system and its performance is compared with the existing methods with the help of simulation results.

1. Introduction

Over the past few years, due to rapid industrialization and increased standard in the life style of the domestic consumers, the electric power requirements have been increasing globally. At the same time, power generating unit's emitting harmful pollutants into the atmosphere. Therefore, the effect of different fuel and carbon prices scenarios is to be investigated under the analysis of the primary energy consumption in the thermoelectric sector [1]. It is well known that electrical energy plays an important role in the national economy; therefore, providing reliable and secure power is one of the important aspects of power system operation and control. In past, many research works have been done in the field of power system security. In Refs. [2], authors utilize auction mechanism in power market to describe a scheme for rescheduling pool generation and adjusting contract-transactions for dynamic security enhancement when necessary. Dynamic security constrained economic dispatch using the transient energy margin has been introduced in Ref. [3]. Authors, in Refs. [4], proposed MMP (Multi-objective Mathematical Programming) model which includes generation cost, CTE (Corrected Transient Energy) margin as dynamic security index and VSM (Voltage Stability Margin) as the voltage security index in the objective function. The power system security deals with the security of the system under a particular operating condition, but when the system is under normal operating condition, the economic aspect of the power system is the primary concern.

The sources of energy (coal, river water, marine tide, a wind energy, sun power, oil, etc.) are so diverse, that the choice of one or the other is made on economical, technical and/or geographical basis. Thus it has become a challenging task for the power utilities to perform proper scheduling of the generating units to minimize the total operating cost [5]. This scheduling process is known as UC (Unit Commitment). The main task of unit commitment problem involves scheduling the ON (1)/OFF (0) status of units, as well as the real power output of generating units to satisfy the forecasted demand over a short-term period, meeting all kinds of system and unit constraints to minimize the overall production cost.

The UC performs an important role in the operational planning of modern power system and saves significant amount of total operation cost per year. Various methods have been proposed in the past, to solve the unit commitment problem, such as PL (Priority List) [6], DP (Dynamic Programming) [7], BB (Branch-and-Bound) [8], and LR (Lagrangian Relaxation) approach [9], etc. These methods are known as classical or numerical optimization

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Nomenclature

a_i, b_i, c_i Cost coefficients of the ith generating unit.
e_i, f_i Valve point coefficients of the ith generating unit.
a_{im}, b_{im}, c_{im} Cost coefficients of the ith generating unit using the fuel type m.
e_{im}, f_{im} Valve point coefficients of the ith generating unit using the fuel type m.
CSC_i/HSC_i Cold/Hot start cost of ith thermal unit.
CSH_i Cold start hour.
$D_{h,j}(t)$ Water discharge rate of jth reservoir at hour t.
$D_{h,j}^{min}/D_{h,j}^{max}$ Minimum/Maximum water discharge rate of jth reservoir.
$F_i(P_i(t))$ Fuel cost function of ith thermal unit at hour t.
F_T Total operation cost over the scheduling horizon.
$I_i(t)$ Schedule state of ith thermal unit for hour t.
I_j Schedule state of jth thermal unit of decommitted group.
I_k Schedule state of kth thermal unit of committed group.
K Total number of units in committed group.
NH Number of hydro units.
NT Number of thermal units.
N_i Number of prohibited zones of ith thermal units.
$P_i(t)$ Generation of ith thermal unit at hour t.
$P^l_{i,m}/P^u_{i,m}$ Lower and upper bounds of ith thermal unit using fuel type m.
$P^l_{i,q}/P^u_{i,q}$ Lower and upper bounds of the qth prohibited zone of ith thermal unit.
$P_i^{max}(t)$ Max generation of ith thermal unit at hour t.
$P_i^{min}(t)$ Min generation of ith thermal unit at hour t.
$P_D(t)$ System load demand at hour t.
$P_{Loss}(t)$ Power network losses at hour t.
$SR(t)$ Spinning reserve requirements at hour t.
$S_{h,j}(t)$ Spillage of jth reservoir at hour t.
RU_i/RD_i Ramp-up/down rate of unit i.
$STC_i(t)$ Startup cost of ith thermal unit at hour t.
$t_{off,i}(t)/t_{on,i}(t)$ Time period that ith thermal unit has been continuously down/up till period t.
T Number of time interval (hours).
$T_{up,i}/T_{down,i}$ Minimum up/down time of ith thermal unit.
$V_{h,j}(t)$ Volume of jth reservoir at hour t.
$V_{h,j}^{min}/V_{h,j}^{max}$ Minimum/Maximum volume of jth reservoir.
$X_{h,j}(t)$ Water inflow rate of jth reservoir at hour t.
γ_j Input/output characteristics of jth hydro unit.

techniques. But the numerical convergence and solution quality problems are the major concerns for most of these approaches.

Some stochastic search methods, such as GA (Genetic Algorithm) [10], BF (Bacteria Foraging) [11], PSO (Particle Swarm Optimization) [12], ICA (Imperialistic Competition Algorithm) [13], ICGA (Integer-Coded Genetic Algorithm) [14], IQEA (Improved Quantum-Inspired Evolutionary Algorithm) [15], HAS (Harmony Search Algorithm) [16], ABC (Artificial Bee Colony Algorithm) [17], BRDE (Binary-Real-coded Differential Evolution) [18] and GMTLBO–BH (Gradient Based Modified Teaching–Learning Optimizer with Black Hole Algorithm) [19] can successfully handle complex nonlinear constraints and provide high-quality solutions, but curse of dimensionality is a major concern. The efforts have also been made to develop hybrid techniques, such as LR with GA (LRGA) [20], LR with PSO (LR-PSO) [21], FAPSO (Fuzzy Adaptive PSO) [22], BCPSO (Binary Clustered PSO) [23], SF (Straight Forward) [24] and THS (Three-Stage) approach [25], for better and faster optimum results.

Several priority list approaches have been proposed with their attention on increasing optimality level and convergence rate. Authors in Ref. [26] proposed a new unit commitment method which uses fast EPL (Extended Priority List) method. The EPL method consists of two steps; in the first step plurality of initial solutions is obtained by PL method and in the second step, several heuristics to plurality of initial solutions are applied for better solution. SPL (Stochastic Priority List) method for solving large-scale unit commitment problem is introduced in Ref. [27]. However, these models usually suffer from the highly heuristic property and relatively poor quality solutions. THS (Three-Stage method) [25], utilized priority list along with AI (Artificial Intelligence) (PSO and Nelder-Mead algorithm) and used for small system without considering unit ramp-rate limit. The simulation results obtained from THS are not very effective.

In past decades, many methods have been proposed to solve short-term hydrothermal unit commitment in power systems such as GA (Genetic Algorithm) [28], SA (Simulated Annealing) [29], DE (Differential Evolution) [30] and DRQEA (differential real coded quantum inspired evolutionary algorithm) [31] etc. Although, above evolutionary methods have shown great strength in solving the non-smooth optimization problems. But, because of their limited local or global search capabilities, they may get trapped in the local optima due to population diversity when handling large-scale problems with highly complex constraints [32]. Compared to other evolutionary techniques, PSO is simple and easy to implement. Furthermore, PSO also has a flexible and well-balanced mechanism for improving and adjusting the global and local search capabilities.

In this paper, an ATHS (Advanced Three-Stage) algorithm is developed for UC (unit commitment) of large systems. A WICPSO (Weight-Improved Crazy Particle Swarm Optimization) along with pseudo-inspired algorithm is proposed for solving the proposed UC problem. The significant contributions of the paper are highlighted as follows:

- ATHS (Advanced Three-Stage) approach is developed. In the first stage, primitive status of all units is obtained on the basis of predefined priority. Second stage utilizes WICPSO along with pseudo-inspired algorithm for accelerating optimization process. In the final stage, SRP (Solution Restructuring Process) is developed to reach an optimum solution.
- The problem formulation incorporates multi-fuel options, prohibited operating zones and nonlinearities due to valve point loading effects. The effectiveness of the proposed approach is demonstrated on several systems including IEEE-118 bus system and results are compared to other techniques available in literature.

2. Problem formulation

The objective of a short-term generation scheduling problem is to minimize thermal unit fuel cost subjected to various system and unit constraints. System configuration and line impedances are not considered in the problem formulation. To perform the proposed approach scheduling period is divided into T time interval and model is formulated as follows:

$$Min\ F_T = \sum_{t=1}^{T}\sum_{i=1}^{NT}[F_i(P_i(t)) + (1 - I_i(t-1) \times STC_i(t))] \times I_i(t) \quad (1)$$

The fuel cost function is assumed as quadratic function of real power output as follows:

$$F_i(P_i(t)) = a_i \times (P_i(t))^2 + b_i \times P_i(t) + c_i \quad (2)$$

The fuel cost function due to valve point loading effect [17] can be expressed as:

$$F_i(P_i(t)) = a_i \times (P_i(t))^2 + b_i \times P_i(t) + c_i + \left|e_i \sin\left(f_i\left(P_i^{min} - P_i(t)\right)\right)\right| \quad (3)$$

Multiple fuels cost function is given as follows:

$$F_i(P_i(t)) = \begin{cases} a_{i1} \times (P_i(t))^2 + b_{i1} \times P_i(t) + c_{i1},\ P_{i,1}^l \le P_i(t) \le P_{i,1}^u & fuel\ 1 \\ a_{i2} \times (P_i(t))^2 + b_{i2} \times P_i(t) + c_{i2},\ P_{i,2}^l \le P_i(t) \le P_{i,2}^u & fuel\ 2 \\ \vdots \\ a_{im} \times (P_i(t))^2 + b_{im} \times P_i(t) + c_{im},\ P_{i,m}^l \le P_i(t) \le P_{i,m}^u & fuel\ m \end{cases} \quad (4)$$

subjected to the following constraints:

Power balance constraint

$$\sum_{i=1}^{NT} I_i(t) \times P_i(t) + \sum_{j=1}^{NH} P_{h,j}(t) = P_D(t) + P_{Loss}(t) \quad (5)$$

Assumed power network losses $P_{Loss}(t) = 0$.

Thermal constraints:

$$\sum_{i=1}^{NT} I_i(t) \times P_i(t) + \sum_{j=1}^{NH} P_{h,j}(t) \ge P_D(t) + P_{Loss}(t) + SR(t) \quad (6)$$

$$\begin{aligned} &P_i^{\min}(t) \le P_i(t) \le P_{i,1}^l(t) \\ &P_{i,q-1}^u(t) \le P_i(t) \le P_{i,q}^l(t) \quad q = 2 \ldots N_i \\ &P_{i,N_i}^u(t) \le P_i(t) \le P_i^{\max}(t) \end{aligned} \quad (7)$$

$$P_i^{\max}(t) = \min(P_i^{\max}, P_i(t-1) + \tau \cdot RU_i) \quad \forall i \in NT \quad (8)$$

$$P_i^{\min}(t) = \max\left(P_i^{\min}, P_i(t-1) - \tau \cdot RD_i\right) \quad \forall i \in NT \quad (9)$$

$$t_{on,i}(t) \ge T_{up,i} \quad (10)$$

$$t_{off,i}(t) \ge T_{down,i} \quad (11)$$

$$STC_{i,t} = \begin{cases} HSC_i & T_{down,i} \le t_{off,i}(t) \le T_{down,i} + CSH_i \\ CSC_i & t_{off,i}(t) > T_{down,i} + CSH_i \end{cases} \quad (12)$$

where, τ is a UC time step which is equal to 60 min.

Hydro constraints:

$$V_{h,j}(t+1) = V_{h,j}(t) + X_{h,j}(t) - D_{h,j}(t) - S_{h,j}(t) \quad (13)$$

$$V_{h,j}(1) = V_{h,j}^{begin} \quad (14)$$

$$V_{h,j}(T) = V_{h,j}^{end} \quad (15)$$

$$P_{h,j}(t) = \gamma_j \times D_{h,j}(t) \quad (16)$$

$$V_{h,j}^{\min} \le V_{h,j}(t) \le V_{h,j}^{\max} \quad \forall j \in NH \quad (17)$$

$$D_{h,j}^{\min} \le D_{h,j}(t) \le D_{h,j}^{\max} \quad \forall j \in NH \quad (18)$$

3. Proposed algorithm

ATHS (Advanced Three-Stage) approach is proposed to obtain the optimal solution of the UC problem in 24-hr of scheduling horizon. To solve the UC problem, time period is divided into smaller time steps of 1-hr each. The proposed approach, in this paper, is divided in to three different stages which are as follows:

3.1. First stage: primitive structure of all units

3.1.1. Priority list

The priority list is created on the basis of minimum per unit cost and maximum power output of units (P_i^{max}). The best per unit cost of units is a function of fuel cost coefficients and is derived using (2). The per unit fuel cost of an *i*th unit will be

$$\frac{F_i}{P_i} = a_i P_i + b_i + \frac{c_i}{P_i} \quad (19)$$

For minimum per unit cost, first derivative of (19) should be zero, i.e.

$$\frac{d}{dP_i}\left(\frac{F_i}{P_i}\right) = 0$$

$$i.e. \quad -\frac{c_i}{P_i^2} + a_i = 0$$

$$i.e. \quad P_i = \sqrt{\frac{c_i}{a_i}} \quad (20)$$

$$\text{Hence, the minimum per unit cost} = 2\sqrt{c_i a_i} + b_i \quad (21)$$

$$\text{Priority list (PList)} = 2\sqrt{c_i a_i} + b_i / P_i^{\max} \quad (22)$$

Primitive structure of all units is decided on a rule that till the spinning reserve has not been satisfied, all the allowable units for

```
ξ(t) = −P_L(t)
for t=1: T
    for i=1:NT
        while ξ(t)<SR(t)
            I(P_List(i),t)=1
            ξ(t)=ξ(t)+ P^max(P_List(i),t)
        end
    end
end
```

Fig. 1. Pseudo code of primary unit scheduling.

any hour of scheduling are turned on according to predefined priority given by (22). The pseudo code of primary unit scheduling computation is shown in Fig. 1.

The units are allowed to change the status only if they are not satisfying the time constraints (10–11). The violation of these constraints requires repairing which is done using heuristic search algorithm. Meeting the time constraint may violate the spinning reserve constraint. This constraint is satisfied in the second stage.

3.1.2. Repairing time constraint

$$t_{on,off,i}(t) = \begin{cases} t_{on,i}(t-1)+1 & if \quad I_i(t)=1 \\ t_{off,i}(t) = -1 & if \quad I_i(t)=0 \end{cases}$$
$$t_{on,off,i}(t) = \begin{cases} t_{off,i}(t-1)-1 & if \quad I_i(t)=0 \\ t_{on,i}(t) = 1 & if \quad I_i(t)=1 \end{cases} \tag{23}$$

The procedure is as follows:

Step 1: ON/OFF time for all units is calculated using (23) for the whole schedule time horizon.
Step 2: Set $t = 1$.
Step 3: Set $i = 1$.
Step 4: If $I_i(t) = 0$, $I_i(t-1) = 1$and $t_{on,i}(t-1) \geq T_{up,i} - t_{on,i}(t-1)$, set $I_i(t) = 1$ else $I_i(t-1) = 0$ (see Fig. 2(a) and (b).
Step 5: If $I_i(t-1) = 0$, $I_i(t) = 1$and $t_{off,i}(t-1) < T_{down,i}$, find $\delta = t_{off,i}(t-1)$ set $\sum_{q=1}^{\delta} I_i(t-q) = 1$ (see Fig. 2(c)).
Step 6: ON/OFF times for the unit i is updated using (23).
Step 7: If $i < NT$, $i = i + 1$ and return to step 4.
Step 8: If $t < T$, $t = t + 1$ and return to step 3. Otherwise, stop and use unit schedule for next stage.

3.2. Second stage: economic dispatch on generating units

3.2.1. Existing approach

The PSO is a meta-heuristic population based optimization technique developed by Eberhart and Kennedy in 1995 [33] inspired by behavior of bird flocks, which can be applied to a multivariable problems which contains many local optimal points. Each particle behaves according to two simple rules to update its velocity and position, respectively: 1) to follow its own achieved successes i.e. to move towards the best solution found by the particle itself *Pbest*; 2) to emulate the success of neighboring particles i.e. to follow the best performing particle in the entire population *Gbest*. By this process, all particles reach to a global optimal solution. In each iteration, velocity v_{ix} and position l_{ix} of the *i*th particle of *x*-dimensional search space are calculated as follows,

$$v_{ix}^{k+1} = w \times v_{ix}^k + c_1 \times rand_1 \times \left(Pbest^k{}_{ix} - l_{ix}^k\right) + c_2 \times rand_2 \times \left(Gbest^k{}_{gx} - l_{ix}^k\right) \tag{24}$$

$$l_{ix}^{k+1} = l_{ix}^k + v_{ix}^{k+1} \tag{25}$$

Inertia weight (w) is set as follows:

$$w = (w_{\max} - w_{\min}) \times \frac{iter_{\max} - iter}{iter_{\max}} + w_{\min} \tag{26}$$

Premature convergence is one of the main problems in the classical PSO. To remove this problem, a CPSO (Crazy Particle Swarm Optimization) was introduced in Ref. [34]. Authors in Ref. [35] utilized PSO with crazy particles to address the premature convergence behavior of classical PSO by re-initialization of the velocity vector for non-convex economic dispatch problem. The CPSO is implemented on the idea of “crazy particles” and “probability of craziness” which are obtained after randomizing velocity of particles. The probability of craziness ρ_{cr} is defined by the following equation:

$$\rho_{cr} = w_{\min} - \exp\left(\frac{-w}{w_{\max}}\right) \tag{27}$$

Thus, velocity is given as [34,35]:

$$v_{ix} = \begin{cases} rand(0, v_{\max}); & if \quad \rho_{cr} > rand(0,1) \\ = v_{ix} & \text{Otherwise} \end{cases} \tag{28}$$

$w_{max} = 0.9$, $w_{min} = 0.4$ and acceleration constants $c_1 = 2$, $c_2 = 2$. where, *iter* is present iteration and $iter_{max}$ is maximum iteration count.

Authors, in Ref. [36] found that classical PSO is not very effective for tracking the dynamic systems. So, they introduce WIPSO (Weighted Improved Particle Swarm Optimization) inspired on the concept of adjusting the inertia weight and acceleration coefficients. Inertia weight and acceleration coefficient are varied according to (30–32). To handle equality constraint, penalty function method is used.

The velocity-update (24) using the modified inertia weight factor i.e. using the WIPSO method can be rewritten as:

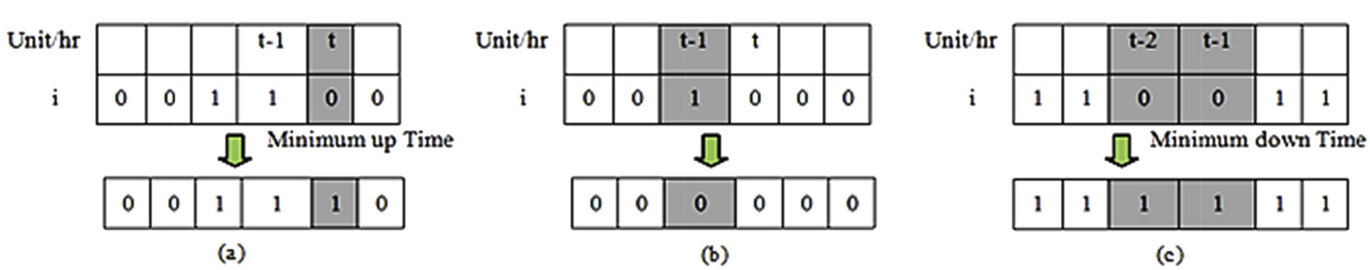

Fig. 2. Reparing of minimum up and down time constraint.

$$v_{ix}^{k+1} = w_{new} \times v_{ix}^{k} + c_1 \times rand_1 \times \left(Pbest^{k}{}_{ix} - l_{ix}^{k}\right) + c_2 \times rand_2 \times \left(Gbest^{k}{}_{gx} - l_{ix}^{k}\right) \quad (29)$$

where,

$$w_{new} = w_{\min} + w*rand \quad (30)$$

where, w is calculated using Equation (26).

$$c_1 = c_{1\max} - (c_{1\max} - c_{1\min})*(iter/iter_{\max}) \quad (31)$$

$$c_2 = c_{2\max} - (c_{2\max} - c_{2\min})*(iter/iter_{\max}) \quad (32)$$

3.2.2. Proposed approach

To gain the different advantages of the various existing methods (PSO, CPSO and WIPSO) discussed in Sub-section 3.2.1, these methods are clubbed together to form a new proposed approach named as WICPSO. Furthermore, in this proposed approach, we have made following modifications:

- Instead of constant/linearly decreasing coefficients, random acceleration coefficients (cognitive and social) within the range are used, and
- Cognitive component is split into two different components (Pbest and Pworst) [37].

With these modifications, the particles are made to remember not only its previous best position but also its previous worst position, while calculating its new velocity. The knowledge about the worst position helps particles in avoiding further movement towards the worst solution. The objective of these modifications is to enhance the global search in the initial stage of the optimization process. Also, it encourages the particles to converge towards the global optima at the end of the search. The velocity vector in the proposed approach is computed as follows:

$$v_{ix}^{k+1} = w_{new} \times v_{ix}^{k} + c_{1newb} \times rand_1 \times \left(Pbest^{k}{}_{ix} - l_{ix}^{k}\right) + c_{1newg} \times rand_2 \times \left(l_{ix}^{k} - Pworst^{k}{}_{ix}\right) + c_{2new} \times rand_3 \times \left(Gbest^{k}{}_{gx} - l_{ix}^{k}\right) \quad (33)$$

where,

$$w_{new} = w_{\min} + w*rand \quad (34)$$

A method of linearly decreasing acceleration coefficients (cognitive and social) with time has been suggested in Refs. [38], but it was found that the fixed acceleration coefficients of two generate better solutions. Moreover, it is suggested through empirical studies, that the acceleration coefficients should not be equal to two every time. Looking at these concerns, this paper proposes random varying acceleration coefficients for WICPSO.

Mathematical model of random varying acceleration coefficients are as follow:

$$c_{1new(g,b)} = c_{1\min} + c_1*rand \quad (35)$$

$$c_{2new} = c_{2\min} + c_2*rand \quad (36)$$

$rand$, and $rand_{1,2and3}$, are uniform random numbers between (0, 1).where, c_1 and c_2 are calculated using (31) and (32). The cognitive coefficient c_{1newg} and c_{1newb} in (33) help the particle to accelerate towards its best position and away from its worst position. The comparison of acceleration coefficients of PSO, CPSO, WIPSO and WICPSO is shown in Fig. 3.

The probability of craziness ρ_{cr} in (27) using the modified inertia weight (w_{new}) can be rewritten as:

$$\zeta_{crm} = w_{\min} - \exp\left(\frac{-w_{new}}{w_{\max}}\right) \quad (37)$$

Thus, velocity is given as:

$$\begin{aligned} v_{ix} &= rand(0, v_{\max});\ if \quad \zeta_{crm} > rand(0,1) \\ &= v_{ix} \qquad\qquad\qquad \text{Otherwise} \end{aligned} \quad (38)$$

3.2.3. Development of the proposed algorithm with hydrothermal scheduling

Let population size be λ and $\lambda_l = [D_{h1}, D_{h2}, \ldots D_{hn} \ldots D_{hNH}]$ be the pilot matrix representing the lth individual population to be derived where, $D_{hj} = [D_{hj1}, D_{hj2}, \ldots D_{hjt} \ldots D_{hjT}]$. The element D_{hjt} is the discharge rate of jth hydro unit at time t. Assuming, the spillage in (13) to be zero for the simplicity, the hydro discharge at dependent interval d can be expressed as

$$D_{h,j}(d) = V_{h,j}(0) - V_{h,j}(T) + \sum_{t=1}^{T} X_{h,j}(t) - \sum_{\substack{t=1 \\ t \neq d}}^{T} D_{h,j}(t) \quad (39)$$

The dependent discharge rate must satisfy the constraints given in (18). Hydro power generation can be calculated using (16) with water discharge obtained from (39). Now from calculated hydro power $P_{h,j}(t)$, the thermal generation P_i for same time period can be obtained as follows:

$$\sum_{i=1}^{NT} P_i(t) = P_D(t) + P_{Loss}(t) - \sum_{j=1}^{NH} P_{h,j}(t) \quad (40)$$

3.2.4. Pseudo code algorithm

There are two methods to handle the constraints in an optimization problem: repairing method (pseudo code algorithm [39]) and penalty function method. In the repairing method, the violations occurred are repaired iteratively, till the equality constraints are satisfied. In the penalty function method, the constrained problem is transformed into unconstrained problem. Nevertheless it suffers from the limitation of reduction in search space (feasible area) due to which it requires high execution time to find the feasible solutions in highly constraint problem. Therefore, in the present work, equality constraint is handled by pseudo code based algorithm [40].

Flow chart of first two stages is given in Fig. 4. Solution obtained by previous two stages may not be acceptable and optimal in most of the time. So final stage called as solution restructuring process is developed to reach to an optimum solution.

3.3. Final stage: SRP (solution restructuring process)

The solution obtained from previous two stages may not be optimal. Therefore final stage introduces a restructuring process on the obtained solution to decrease the total operational cost of the system while satisfying different system and unit constraints. Because of the long T_{up}, T_{down} hours and startup cost of large units, it is more expensive to use them in short horizon of time. Thus, it is reasonable to use them as a base-load unit. The small units with

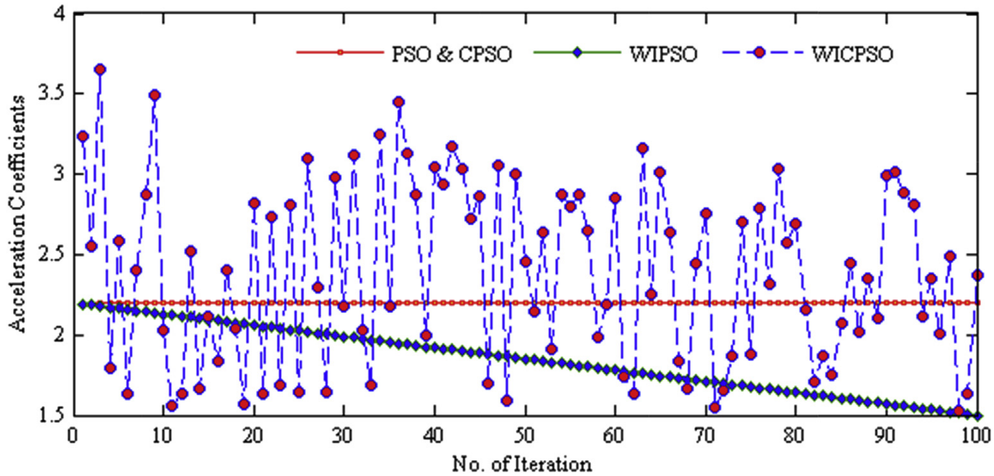

Fig. 3. Comparison of acceleration coefficient by different PSO variants.

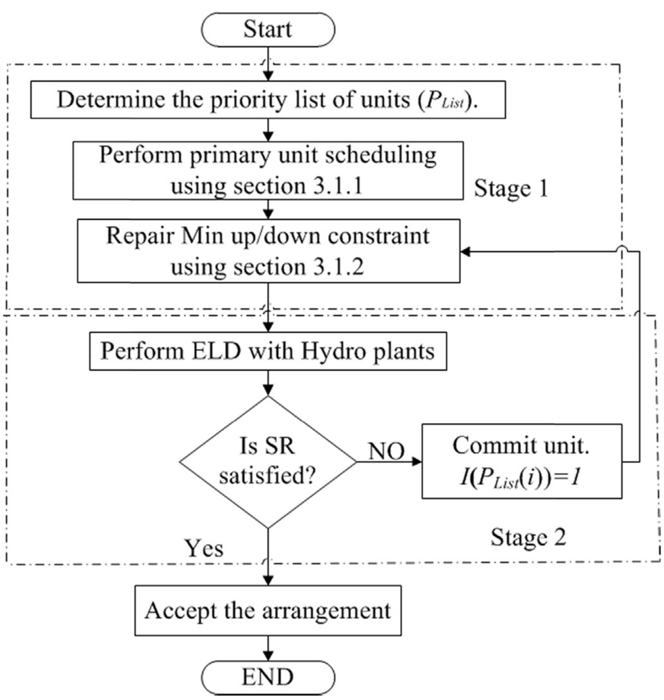

Fig. 4. Flow chart of first two stages.

small T_{up}, T_{down} and startup cost is preferred for peak-load units. Fig. 5 shows load profile for 24-hr.

The procedure for SRP is as follows:

a) At each hour, two groups are formed known as DG (Decommitment Group) and CG (Commitment Group) with units that are allowed to be turned OFF and turned ON, respectively.
b) Finally, reshuffling of the units belonging to the DG and CG is done to minimize the total operating cost (F_T). Fig. 6 describes solution restructuring process in detail.

Reshuffling of the units from one group to another (DG and CG) is based on its priority as defined in Sub-section 3.1.1. The units with larger value of per unit cost (21) are decommitted first in DG. The units with smaller value of per unit cost (21) are committed first in CG. Modification process on primary configuration (solution obtained from first two stages) of THS [25] and restructuring process of the proposed approach ATHS is compared in Fig. 7. It is found that there is only one modification needed (third stage) in case of proposed approach as compared to THS where as five modifications are needed for ten units system with 5% spinning reserve. SRP of the proposed ATHS approach for ten units system with 10% spinning reserve is shown in Fig. 8. In 22nd hour, 3rd unit and 4th unit are decommitted from DG. Similarly, in 23rd hour, 5th unit from DG is decommitted and 6th unit from CG is committed. Square and elliptical shapes present the units of DG and CG, respectively.

4. Test results

The proposed approach is tested to solve a standard large scale UC problem. To validate the performances of the proposed approach, six different tests are conducted. The parameters of WICPSO are as follows [37]:

- Population size = 20 to 100.
- Maximum velocity = P_i^{max}.
- Minimum velocity = P_i^{min}.
- $w_{max} = 1.2$ and $w_{min} = 0.3$.
- $c_{1\min} = 1.5$, $c_{1\max} = 2.2$, $c_{2\min} = 1.5$, $c_{2\max} = 2.2$.
- Maximum iteration = 1000.

4.1. Test-1

In this test, four thermal units are considered. Load demand data, unit characteristics and cost coefficients are taken from Ref. [25]. Here, system is tested for 10% of spinning reserve. Comparison of simulation results from proposed approach with other techniques available in literature is shown in Table 1. It can be observed that proposed approach provides better results in comparison to other existing techniques.

4.2. Test-2

In this test, ten thermal units are considered. The data of 10-unit system and load are taken from Ref. [11]. The spinning reserve is set to be 5% of the load demand. The generator ramp-up constraints are set at 70% of its rated capacity. Simulation results, after SRP, are compared with other techniques available in literature is shown in

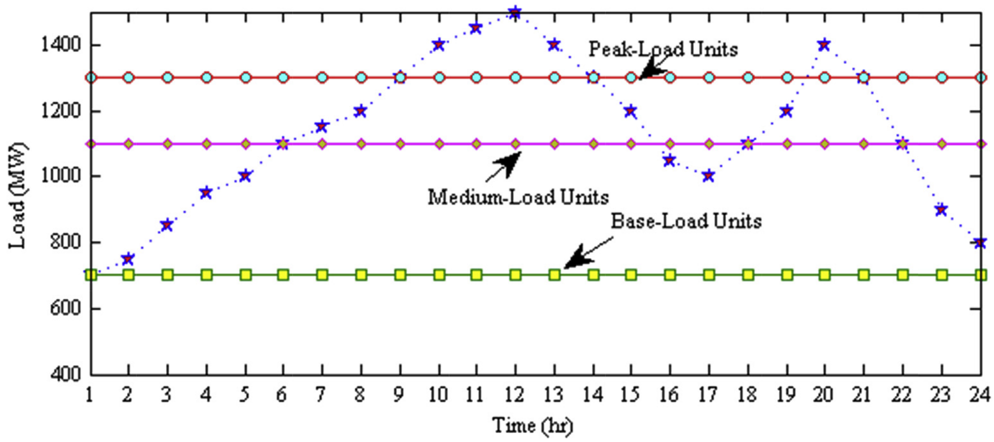

Fig. 5. Load profile curve.

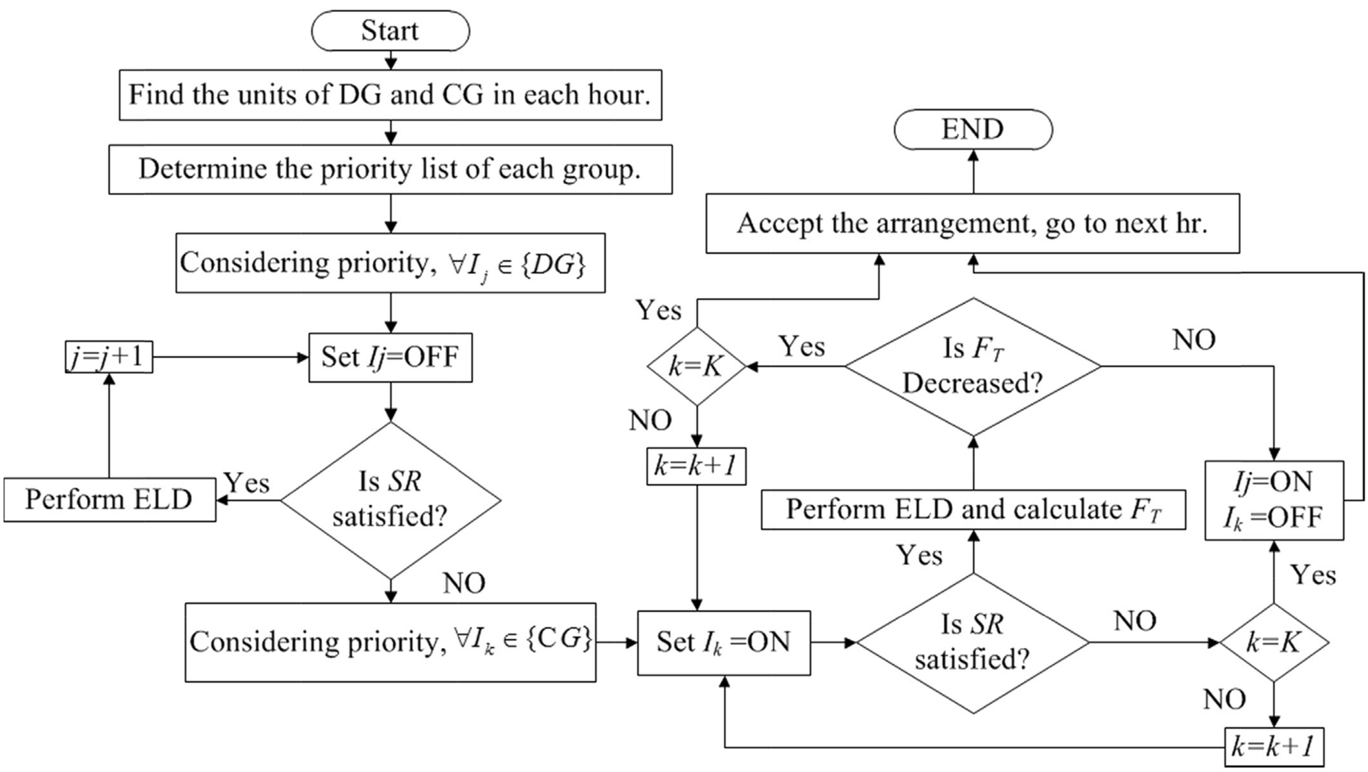

Fig. 6. Flow chart of the SRP.

Table 2. It can be observed that the results are same before and after SRP for this test.

To test the effectiveness of the proposed algorithm, ATHS with proposed WICPSO used in second stage is compared with three different versions of PSO as discussed in Sub-section 3.2.1. Tables 1 and 2 depict the results, obtained from different versions of PSO. Thus, it is found that all the versions of PSO used to give the same cost but the time of execution is less with the WICPSO. Convergence curves for Test 2 with different PSO variants are shown in Fig. 9. It can be observed that all the four PSO variants converge to the optimum solution, but the convergence of proposed WICPSO technique is faster as compared to other PSO variants. To demonstrate the effectiveness of ATHS with WICPSO, it is applied to large scale power system.

4.3. *Test-3*

By duplicating the amounts of ten units system, we can define large scale UC problem with 20, 40, 60, 80 and 100 generating units, considering a time horizon of 24 hr. The spinning reserve is set to be 10% of the load demand. The generator ramp-up constraints are set at 81% of its rated capacity. Ten simulations have been performed for this test.

Comparison of cost after SRP with the existing methods is shown in Table 3. From Table 3, it can be observed that the solutions of the proposed approach are more effective with higher units. Fig. 10 shows the convergence characteristic of WICPSO for units ranging from 10 to 100, with and without ramp-rate limit. The ON/OFF result of ATHS with a total operating cost of $5, 601,651

Hour\ Units	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
1	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	455	395	0	0	0	0	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	455	455	0	0	40	0	0	0	0	0	455	455	0	0	40	0	0	0	0	0
5	455	455	0	0	90	0	0	0	0	0	455	455	0	0	90	0	0	0	0	0
6	455	455	0	130	60	0	0	0	0	0	455	455	0	130	60	0	0	0	0	0
7	455	410	130	130	25	0	0	0	0	0	455	410	130	130	25	0	0	0	0	0
8	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
9	455	455	130	130	110	20	0	0	0	0	455	455	130	130	110	20	0	0	0	0
10	455	455	130	130	162	43	25	0	0	0	455	455	130	130	162	43	25	0	0	0
11	455	455	130	130	162	80	25	13	0	0	455	455	130	130	162	80	25	13	0	0
12	455	455	130	130	162	80	25	53	10	0	455	455	130	130	162	80	25	53	10	0
13	455	455	130	130	162	43	25	0	0	0	455	455	130	130	162	43	25	0	0	0
14	455	455	130	130	110	20	0	0	0	0	455	455	130	130	110	20	0	0	0	0
15	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
16	455	310	130	130	25	0	0	0	0	0	455	310	130	130	25	0	0	0	0	0
17	455	260	130	130	25	0	0	0	0	0	455	260	130	130	25	0	0	0	0	0
18	455	360	130	130	25	0	0	0	0	0	455	360	130	130	25	0	0	0	0	0
19	455	455	130	130	30	0	0	0	0	0	455	455	130	130	30	0	0	0	0	0
20	455	455	130	130	162	43	25	0	0	0	455	455	130	130	162	48	0	10	10	0
21	455	455	0	130	162	73	25	0	0	0	455	455	0	130	110	20	0	0	0	0
22	455	455	0	0	145	20	25	0	0	0	455	455	0	130	40	20	0	0	0	0
23	455	425	0	0	0	20	0	0	0	0	455	425	0	0	0	20	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0

Fig. 7. SMP of THS on left side and SRP of ATHS on right side of the fig, (10 unit system with 5% spinning reserve).

Hour\ Units	1	2	3	4	5	6	7	8	9	10	Hour\ Units	1	2	3	4	5	6	7	8	9	10
1	455	245	0	0	0	0	0	0	0	0	13	455	455	130	130	162	33	25	10	0	0
2	455	295	0	0	0	0	0	0	0	0	14	455	455	130	130	85	20	25	0	0	0
3	455	370	0	0	25	0	0	0	0	0	15	455	455	130	130	30	0	0	0	0	0
4	455	455	0	0	40	0	0	0	0	0	16	455	310	130	130	25	0	0	0	0	0
5	455	390	0	130	25	0	0	0	0	0	17	455	260	130	130	25	0	0	0	0	0
6	455	360	130	130	25	0	0	0	0	0	18	455	360	130	130	25	0	0	0	0	0
7	455	410	130	130	25	0	0	0	0	0	19	455	455	130	130	30	0	0	0	0	0
8	455	455	130	130	30	0	0	0	0	0	20	455	455	130	130	162	33	25	10	0	0
9	455	455	130	130	85	20	25	0	0	0	21	455	455	130	130	85	20	25	0	0	0
10	455	455	130	130	162	33	25	10	0	0	22	455	455	0	0	145	20	25	0	0	0
11	455	455	130	130	162	73	25	10	10	0	23	455	425	0	0	0	20	0	0	0	0
12	455	455	130	130	162	80	25	43	10	10	24	455	345	0	0	0	0	0	0	0	0

Fig. 8. Solution restructuring process on a 10 unit system with 10% spinning reserve.

(without ramp rate) and $ 5,617,508 (with ramp rate) for the 100-unit test system is presented in Table 4. The unit status with underlines is only for the ramp rate condition. All other unit status is common for both with and without ramp rate condition.

The results of proposed approach for 10 to 100 generating units with execution time and RSD (relative standard deviation) are shown in Table 5. The proposed approach is further utilized to solve a UC problem with ramp rate limits. All the online units will operate

Table 1
Cost comparison for Test 1.

Methods	Total cost ($)	Time (s)
LR [9]	75,232	–
PSO-LR [9]	74,808	–
THS [25]	74,812	–
ATHS (PSO)	74,525	1.86
ATHS (WIPSO)	74,525	1.72
ATHS (CPSO)	74,525	1.68
ATHS (WICPSO)	74,525	1.53

Table 2
Cost comparison for Test 2.

Methods	Without ramp		With ramp	
	Total cost ($)	Time (s)	Total cost ($)	Time (s)
GA [10]	570,781	–	–	–
BP [43]	565,450	–	–	–
APSO [43]	561,586	–	–	–
THS [25]	557,677	–	–	–
ATHS (PSO)	557,128	8.82	559,350	9.92
ATHS (WIPSO)	557,128	8.36	559,350	9.43
ATHS (CPSO)	557,128	7.73	559,350	8.35
ATHS (WICPSO)	557,128	6.58	559,350	6.94

within their feasible output limits by handling their ramp rate limit as explained in Ref. [41]. Cost with execution time and RSD of result is shown in Table 6. From Table 6 it is found that due to the incorporation of thermal unit ramp-rate characteristic in the problem, the generating cost and execution time both are increased. Fig. 11 shows ramp-rate characteristic of ten thermal units system (U1–U10) in a time horizon of 24-hr. In Fig. 11, the ramp-rate characteristics of first two units are not shown, as these two units are acting as base-load units of the system as shown in Fig. 5.

Although the execution times (CPU time) with different techniques shown in Table 7 may not be directly comparable due to variation of system configuration or programming languages, but some observation can be attain. From Table 7, it can be observed that, ATHS provide better solution with much lower execution times compared to the GA, BF, ICA, HAS, LRGA, DPLR, PSO, IPSO and UCC-GA methods. Although, ATHS requires more time in comparison with IQEA, ICGA, and ELRPSO but the quality of the final results is much better than the results obtained using ICGA, IQEA, and ELRPSO.

4.4. Test-4

The system data for this test is same as that in Test 3. However, in this test system, units 1, 2, 8 and 10 exhibit POZ (Prohibited Operating Zone) [42]. The result of the generation scheduling of proposed approach for a ten generating units, with and without POZ is given in Table 8. Values in bold and italic are the changes achieved after incorporation of POZ. Table 9 provides the best operating cost and execution time for large scale UC problem under POZ.

4.5. Test-5

This test has been performed on the IEEE 118-bus system [17]. In this test, two different cases are performed. In Case 1, ramp rate

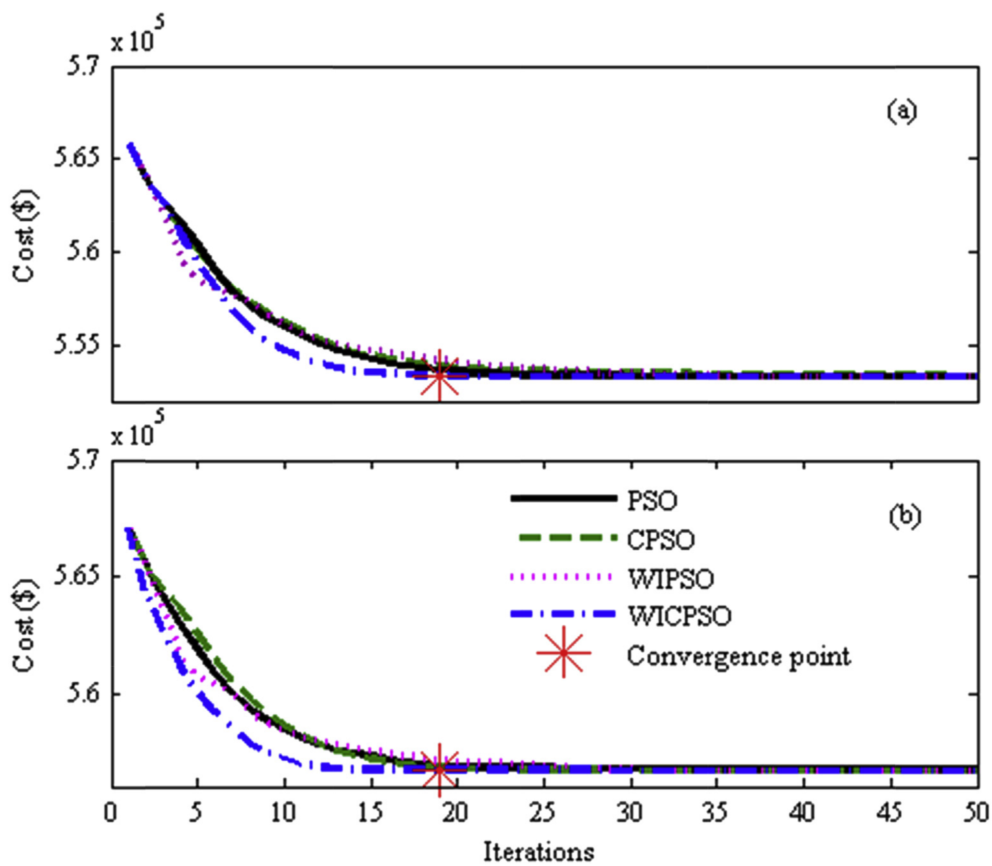

Fig. 9. Convergence characteristics with different PSO variant (a) Without Ramp Rate (b) With Ramp Rate.

Table 3
Cost comparison for Test 3.

Methods	10-unit	20-unit	40-unit	60-unit	80-unit	100-unit
GA [24]	565,825	1,126,243	2,251,911	3,376,625	4,504,933	5,627,437
BF [11]	565,872	1,128,112	2,255,112	3,379,120	4,508,762	5,632,491
PSO [12]	564,212	1,125,983	2,250,012	3,374,174	4,501,538	5,625,376
IPSO [12]	563,954	1,125,279	2,248,163	3,370,979	4,495,032	5,619,284
BCPSO [23]	563,947	1,123,781	2,266,040	3,373,258	4,498,037	5,600,975
FAPSO [22]	564,163	1,123,512	–	–	–	–
ICGA [14]	566,404	1,127,244	2,254,123	3,378,108	4,498,943	5,630,838
ICA [13]	563,938	1,124,274	2,247,078	3,371,722	4,497,919	5,617,913
QEA-UC [15]	563,938	1,123,607	2,245,557	3,366,676	4,488,470	5,609,550
IQEA [15]	563,938	1,123,297	2,242,980	3,362,010	4,482,826	5,602,387
HAS [16]	565,827	1,127,177	2,250,968	3,375,138	4,500,745	5,622,350
DE [18]	563,446	1,123,397	2,244,177	3,364,013	4,485,571	5,604,196
GMTLBO-BH [19]	563,938	1,123,297	2,245,602	–	–	5,611,105
ELRPSO [21]	563,938	1,123,297	2,243,256	3,361,573	4,482,937	5,601,825
SF [24]	563,865	1,122,622	2,242,178	3,363,491	4,485,633	5,605,189
EPL [26]	563,977	1,124,369	2,246,508	3,366,210	4,489,322	5,608,440
SPL [27]	564,950	1,123,938	2,248,645	3,371,178	4,492,909	5,615,530
THS [25]	563,938	1,124,490	–	–	–	–
ATHS	563,938	1,123,297	2,242,957	3,361,748	4,482,417	5,601,651

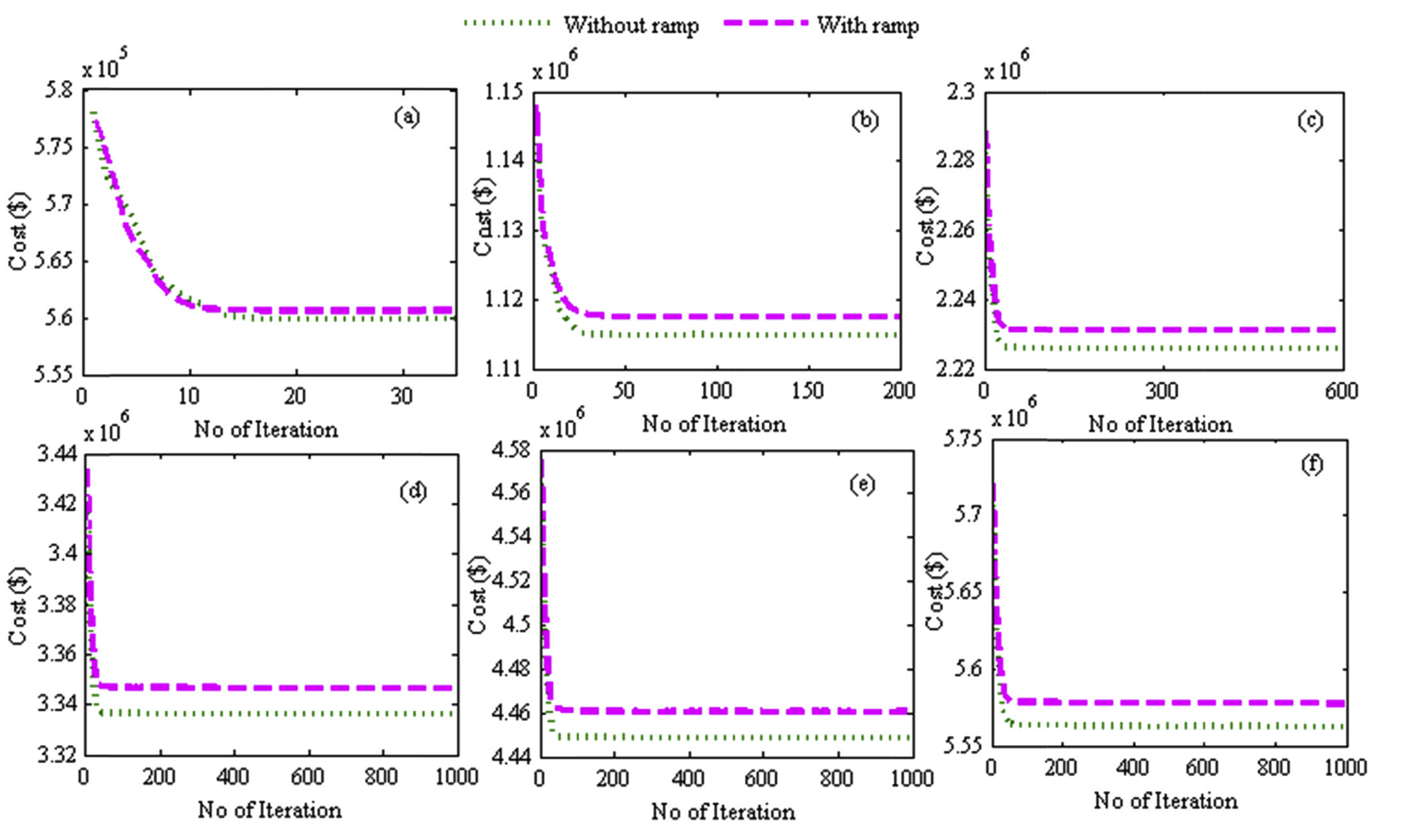

Fig. 10. Convergence characteristics with and without ramp-rate for systems with different number of units for test 3, (a) 10 units, (b) 20 units, (c) 40 units (d) 60 units, (e) 80 units and (f) 100 units.

constraint along with the spinning reserve is taken into account and transmission losses are neglected. In Case 2, non-linearity in fuel cost function, multi fuel constraint, prohibited operating zones and transmission losses are also considered. Comparison of simulation results from proposed approach with other techniques available in literature is shown in Table 10. It can be observed that proposed approach take more time in comparison to other existing techniques but the quality of the final results is much better.

4.6. Test-6

This test includes 10 thermal units (U1–U10) as same as in Test 2 and two hydro units (H1–H2). Hydro unit's details are taken from Ref. [40]. The spinning reserve is assumed to be 10% of the load demand. The generator ramp-up constraints are set at 60% of its rated capacity. Unit status and simulation results with and without ramp rate is given in Table 11. The unit status with underlines is

Table 4
Unit status with and without ramp-rate.

Units	Hours (1–24)																							
U1–U20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
U21	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U22	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U23–U25	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U26	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U27–U30	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U31	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U32-40	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
U41–U42	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
U43–U45	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
U46–U49	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U50	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U51–U63	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	1	1	0	0
U64–U65	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
U66–U70	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
U71–U78	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0
U79–U82	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0
U83–U88	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0
U89	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0
U90	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0
U91–U98	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
U99–U100	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Note: The unit status with underlines is only for the ramp rate condition. The rests are performed for both with and without ramp rate conditions.

Table 5
Result of proposed method without thermal unit ramp-rate.

No. of units	Cost ($)			RSD (%)	Time (s)
	Best	Mean	Worst		
10	563,938	563,946	564,000	0.00339	10.61
20	1,123,297	1,123,809	1,123,897	0.00383	25.31
40	2,242,957	2,243,000	2,243,089	0.00229	123.36
60	3,361,748	3,361,822	3,361,895	0.00314	328.15
80	4,482,417	4,482,585	4,482,716	0.00275	485.96
100	5,601,651	5,601,855	5,601,937	0.00183	660.57

Table 6
Result of proposed method with thermal unit ramp-rate.

No. of units	Cost ($)			RSD (%)	Time (s)
	Best	Mean	Worst		
10	564,733	564,786	565,240	0.02829	12.41
20	1,125,902	1,125,917	1,126,014	0.00304	35.36
40	2,248,333	2,248,373	2,248,454	0.00186	141.67
60	3,372,355	3,372,407	3,372,562	0.00207	346.43
80	4,494,963	4,495,137	4,495,526	0.00424	518.03
100	5,617,508	5,617,756	5,617,815	0.00254	716.68

only for the ramp rate condition. All other unit status is common for both with and without ramp rate condition. Hydro generation and volumes of reservoir are shown in Fig. 12. From the simulation results, it is found that by efficiently utilizing hydro energy, the total fuel cost of thermal units can be reduced significantly.

5. Conclusions

Proposed ATHS (Advanced Three-Stage Approach) has been successfully applied to solve large scale UC (Unit Commitment) problem considering with and without thermal ramp-rate constraint. The ATHS works on mutual operation of meta-heuristics approach and some of the logical/simple stages to solve the UC problem. In addition, proposed approach considers the multi-fuel options, prohibited operating zones and nonlinearities in the fuel cost due to valve point loading effects. Weighted-improved crazy particle swarm optimization along with pseudo code based algorithm (to deal with the equality constraints) is proposed for accelerating the optimization process. The method is simple, easy to implement and applicable for large-scale systems. The simulation results obtained from the ATHS are compared with other

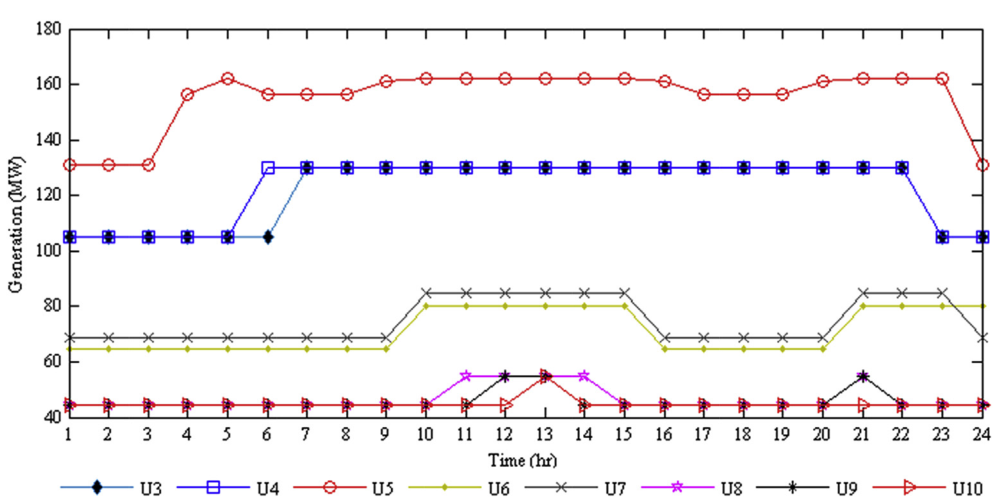

Fig. 11. Ramp-rate characteristics of thermal units.

Table 7
Comparison of execution times.

No. of units	Execution time (s)												
	GA	ICGA	ICA	BF	QEA-UC	HAS	ELRPSO	PSO	IPSO	LRGA	DPLR	UCC-GA	ATHS
10	221	7	48	80	19	6.9	2.46	120	105	518	108	85	10.61
20	733	22	63	210	28	61	4.1	320	300	1147	299	225	25.31
40	2697	58	151	510	43	234	7.19	1300	1050	2165	1200	614	123.36
60	5480	117	366	1100	54	562	9.86	2500	2000	2414	3199	1085	328.15
80	10,036	176	994	2600	66	1103	12.76	4050	3600	3383	8447	1975	485.96
100	15,733	243	1376	4700	80	1911	16.18	6300	5800	4045	12,737	3547	660.57

Table 8
Operation cost and schedule for 24-hr.

Hour	Power generation of units (MW)										Available reserve (%)	Generation cost ($)	Start-up cost ($)	Modification rate ($)
	1	2	3	4	5	6		8	9	10				
1	455/ ***447.99***	245/ ***252.01***	0	0	0	0	0	0	0	0	30.00	13683.13/ ***13688.67***	0	0.00
2	455	295	0	0	0	0	0	0	0	0	21.33	14554.50	0	0.00
3	455	370	0	0	25	0	0	0	0	0	26.12	16809.45	900	0.00
4	455	455	0	0	40	0	0	0	0	0	12.84	18597.67	0	0.00
5	455	390	0	130	25	0	0	0	0	0	20.20	20020.02	560	0.00
6	455	360	130	130	25	0	0	0	0	0	21.09	22387.04	1100	0.00
7	455	410	130	130	25	0	0	0	0	0	15.83	23261.98	0	0.00
8	455	455	130	130	30	0	0	0	0	0	11.00	24150.34	0	0.00
9	455	455	130	130	85	20	25	0	0	0	15.15	27251.06	860	0.00
10	455	455	130	130	162	33	25	10	0	0	10.86	30057.55	60	0.00
11	455	455	130	130	162	73	25	10	10	0	10.83	31916.06	60	0.00
12	455	455	130	130	162	80/ ***77.99***	25	43/ ***45.01***	10	10	10.80	33890.16/ ***33895.99***	60	0.00
13	455	455	130	130	162	33	25	10	0	0	10.86	30057.55	0	0.00
14	455	455	130	130	85	20	25	0	0	0	15.15	27251.06	0	0.00
15	455	455	130	130	30	0	0	0	0	0	11.00	24150.34	0	0.00
16	455	310	130	130	25	0	0	0	0	0	26.86	21513.66	0	0.00
17	455	260	130	130	25	0	0	0	0	0	33.20	20641.82	0	0.00
18	455	360	130	130	25	0	0	0	0	0	21.09	22387.04	0	0.00
19	455	455	130	130	30	0	0	0	0	0	11.00	24150.34	0	0.00
20	455	455	130	130	162	33	25	10	0	0	10.86	30057.55	490	0.00
21	455	455	130	130	85	20	25	0	0	0	15.15	27251.06	0	0.00
22	455	455	0	0	145	20	25	0	0	0	12.45	22735.52	0	857.45
23	455	425	0	0	0	20	0	0	0	0	10.00	17645.36	0	39.33
24	455	345	0	0	0	0	0	0	0	0	13.75	15427.42	0	0.00
Total												559847.69/ ***559859.06***	4090	896.77

Note: Values in bold and italic are the changes achieved after incorporation of POZ.

Table 9
Result of proposed method with prohibited operating zones.

No. of units	Without ramp rate		With ramp rate	
	Total cost ($)	Execution time (s)	Total cost ($)	Execution time (s)
10	563,949	11.12	564,745	13.54
20	1,123,320	28.31	1,126,130	39.96
40	2,243,001	133.36	2,248,452	149.67
60	3,361,786	335.45	3,372,392	376.83
80	4,482,477	493.16	4,495,008	558.63
100	5,601,798	676.57	5,617,612	776.88

Table 10
Result of proposed method for IEEE 118-bus system.

Methods	Case 1		Case 2	
	Total cost ($)	Execution time (s)	Total cost ($)	Execution time (s)
SDP [24]	1,645,445	–	–	–
SF [24]	1,643,818	6.57	–	–
BRABC [17]	1,644,270	276.35	1,773,388	1096.38
ATHS	1,643,395	324	1,773,121	1146.20

Table 11
Result of proposed method for hydrothermal scheduling.

Units	Hours (1–24)																							
U1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
U2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
U3	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
U4	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
U5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
U6	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	1	1	0	0
U7	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
U8	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0
U9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
U10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
H2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Cost ($)												**Execution time (s)**											
Without ramp	502,608												13.82											
With ramp	503,381												15.76											

The unit status with underlines is only for the ramp rate condition. The rests are performed for both with and without ramp rate conditions.

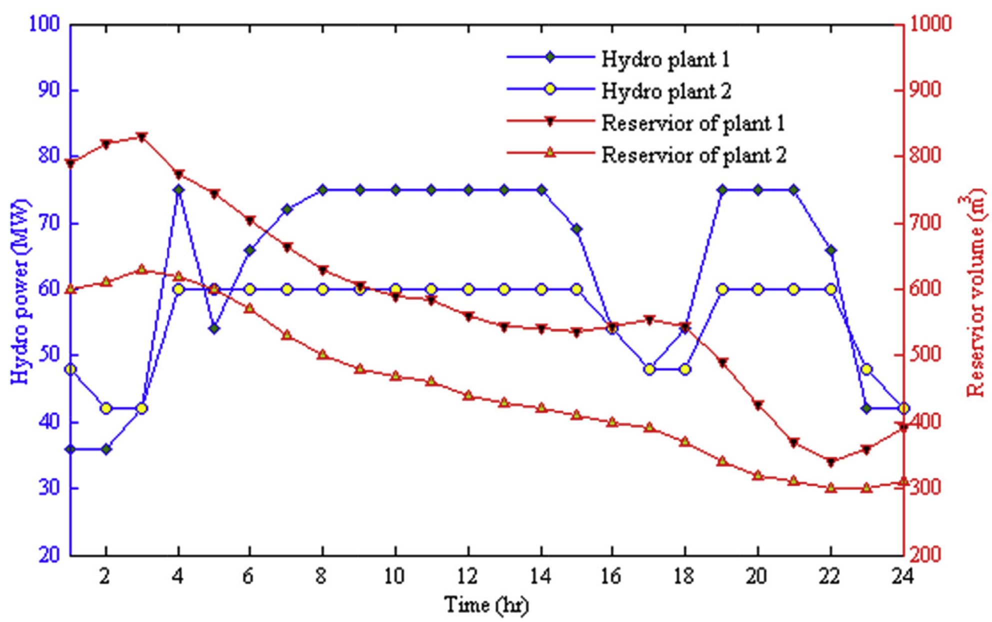

Fig. 12. Hydro plant and reservoir output.

techniques reported in the literature. It is found that the ATHS gives economical solution for large scale UC problem compared to other existing methods, within a reasonable time.

- The minimum cost so far reported in literature for 100 units system [21] is $ 174 higher than that obtained from proposed approach.
- Furthermore, for IEEE-118 bus system, the best total operational cost obtained from proposed approach is 423 $ lower than that reported in literature [24].
- The results verify the proposed approach is feasible and efficient for handling large scale UC problem.

Future research work will focus on the detailed evolution of proposed approach with some improvement to incorporate security constraint in the UC problem.

References

[1] Bianco V, Scarpa F, Tagliafico TA. Long term outlook of primary energy consumption of the Italian thermoelectric sector: impact of fuel and carbon prices. Energy 2015;87:153–64.
[2] Singh SN, David AK. Optimal dispatch in dynamic security constrained open power market. Int J Electr Power & Energy Syst 2002;24(5):363–9.
[3] David AK, Lin X. Dynamic security enhancement in power market systems. IEEE Trans Power Syst 2002;17(2):431–8.
[4] Aghaei J, Shayanfar HA, Amjady N. Multi-objective electricity market clearing considering dynamic security by lexicographic optimization and augmented epsilon constraint method. Appl Soft Comput 2011;11(4):3846–58.
[5] Ji B, Yuan X, Chen Z, Tian H. Improved gravitational search algorithm for unit commitment considering uncertainty of wind power. Energy 2014;67:52–62.
[6] Delarue E, Cattrysse D, D'haeseleer W. Enhanced priority list unit commitment method for power systems with a high share of renewables. Electr Power Syst Res 2013;105:115–23.
[7] Ouyang Z, Shahidehpour SM. An intelligent dynamic programming for unit commitment application. IEEE Trans Power Syst 1999;6(3):1203–9.
[8] Chen CL, Wang SC. Branch-and-bound scheduling for thermal generating units. IEEE Trans Energy Convers 1993;8(2):184–9.
[9] Virmani S, Adrian C, Imhof K, Mukherjee S. Implementation of a Lagrangian relaxation based unit commitment problem. IEEE Trans Power Syst 1989;4(4):1373–80.
[10] Senjyu T, Yamashiro H, Shimabukuro K, Uezato K, Funabashi T. Fast solution technique for large-scale unit commitment problem using genetic algorithm. IEE Proc Gener Transm Distrib 2003;150(6):753–60.
[11] Eslamian M, Hosseinian SH, Vahidi B. Bacterial foraging based solution to the unit commitment problem. IEEE Trans Power Syst 2009;24(3):1478–88.
[12] Zhao B, Guo CX, Bai BR, Cao YJ. Improved particle swarm optimization algorithm for unit commitment. Int J Electr Power Energy Syst 2009;28(7):482–90.

[13] Hadji MM, Vahidi BA. Solution to the unit commitment problem using imperialistic competition algorithm. IEEE Trans Power Syst 2012;27(1):117–24.
[14] Damousis IG, Bakirtzis AG, Dokopoulos PS. A solution to the unit commitment problem using integer-coded genetic algorithm. IEEE Trans Power Syst 2002;19(2):1165–72.
[15] Chung CY, Yu H, Wong KP. An advanced quantum-inspired evolutionary algorithm for unit commitment. IEEE Trans Power Syst 2011;26(2):847–54.
[16] Pourjamal Y, Ravandanegh SN. HAS based solution to the UC problem. Int J Electr Power Energy Syst 2013;46:211–20.
[17] Chandrasekaran K, Hemamalini S, Simon SP, Pandy NP. Thermal unit commitment using binary/real coded artificial bee colony algorithm. Electr Power Syst Res 2012;84(1):109–19.
[18] Datta D, Datta S. A binary-real coded differential evaluation for unit commitment problem. Int J Electr Power Energy Syst 2012;42(1):517–24.
[19] Abarghooee RA, Niknam T, Bavafa F, Zare M. Short-term scheduling of thermal power systems using hybrid gradient based modified teaching-learning optimizer with black hole algorithm. Electr Power Syst Res 2014;108:16–34.
[20] Cheng CP, Liu CW, Liu GC. Unit commitment by Lagrangian relaxation and genetic algorithm. IEEE Trans Power Syst 2000;15(2):707–14.
[21] Yu X, Zhang X. Unit commitment using Lagrangian and particle swarm optimization. Int J Electr Power Energy Syst 2014;61:510–22.
[22] Saber AY, Senjyu T, Yona A, Funabashi T. Unit commitment computation by fuzzy adaptive particle swarm optimization. IEE Proc Gener Transm Distrib 2007;1(3):456–65.
[23] Chakraborty S, Ito T, Senjya T, Saber AY. Unit commitment strategy of thermal generators by using advanced fuzzy controlled binary particle swarm optimization algorithm. Int J Electr Power Energy Syst 2012;43(1):1072–780.
[24] Hosseini SH, Khodaei A, Aminifar F. A novel straightforward unit commitment method for large-scale power system. IEEE Trans Power Syst 2007;22(4):2134–43.
[25] Khanmohammdi S, Amiri M, Tarafdar Haque M. A new three-stage method for solving unit commitment problem. Energy 2010;35:3072–80.
[26] Senjyu T, Shimabukuro K, Uezato K, Funabashi T. A fast technique for unit commitment problem by extended priority list. IEEE Trans Power Syst 2003;18(2):882–8.
[27] Senjyu T, Miyagi T, Saber AY, Urasaki N, Funabashi T. Emerging solution of large-scale unit commitment problem by stochastic priority list. Electr Power Syst Res 2006;76(5):283–92.
[28] Kumar S, Naresh R. Efficient real coded genetic algorithm to solve the non-convex hydrothermal scheduling problem. Int J Electr Power & Energy Syst 2007;29(10):738–47.
[29] Wong KP, Wong YW. Short-term hydrothermal scheduling part. I. simulated annealing approach. IEE Proc Gener Transm Distrib 1994;141(5):497–501.
[30] Lu YL, Zhou JZ, Qin H, Wang Y, Zhang YC. An adaptive chaotic differential evolution for the short-term hydrothermal generation scheduling problem. Energy Convers Manage 2010;51(7):1481–90.
[31] Wong Y, Zhou J, Mo L, Zhang R, Zhang Y. Short-term hydrothermal generation scheduling using differential real-coded quantum–inspired evolutionary algorithm. Energy 2012;44:657–71.
[32] Catalao JPS, Pousinho HMI, Contreras J. Optimal hydro scheduling and offering strategies considering price uncertainty and risk management. Energy 2012;37(1):237–44.
[33] Kennedy J, Eberhart RC. Particle swarm optimization. In: IEEE Proceedings International Conference on Neural Networks, Perth, WA; Dec. 1995. p. 1942–8.
[34] Aruldoss T, Victoire A, Jeyakumar AE. Reserve constrained dynamic dispatch of units with valve point effects. IEEE Trans Power Syst 2005;20(3):1273–82.
[35] Chaturvedi KT, Pandit M, Srivastava L. Particle swarm optimization with crazy particle for non-convex economic dispatch. J Appl Soft Comput 2009;9(3):962–9.
[36] Khokhar B, Parmar KPS. A novel weight-improved particle swarm optimization for combined economic and emission dispatch problem. Int J Eng Sci Technol 2012;4:2015–21.
[37] Selvakumar AI, Thanushkodi K. A new particle swarm optimization solution to non-convex economic dispatch problem. IEEE Trans Power Syst 2007;2(1):1273–82.
[38] Ratnaweera A, Halgamuge S, Watson H. Self-organizing hierarchical particle swarm optimizer with time-varying acceleration coefficients. IEEE Trans Evol Comput 2004;8(3):240–55.
[39] Shukla A, Singh SN. Pseudo-inspired PSO for solving unit commitment problem including renewable energy sources. In: 5th international conference on Power and Energy Systems, Kathmandu, Nepal; Oct. 2013. p. 1–6.
[40] Shukla A, Singh SN. Cluster based wind-hydro-thermal unit commitment using GSA algorithm. In: PES '14 IEEE Power & Energy Society General Meeting, Washington DC; Jul. 2014. p. 1–5.
[41] Wang C, Shahidehpour SM. Effects of ramp-rate limits on unit commitment and economic dispatch. IEEE Trans Power Syst 1993;8(3):1341–50.
[42] Kasmaei MP, Nejad MR, Abdollahi A. A novel unit commitment technique considering prohibited operating zones. J Appl Sci 2009;9(16):2962–7.
[43] Pappala VS, Erlich I. A new approach for solving the unit commitment problem by adaptive particle swarm optimization. In: Power and Energy Society general meeting-conversion and delivery of electrical energy in the 21st century, Pittsburg; Jul. 2008. p. 1–6.