Short Term Economic Emission Power Scheduling of Hydrothermal Energy Systems Using Improved Water Cycle Algorithm

SHAIKH SAAQIB HAROON, AND TAHIR NADEEM MALIK*

RECEIVED ON 09.09.2015 ACCEPTED ON 11.05.2016

ABSTRACT

Due to the increasing environmental concerns, the demand of clean and green energy and concern of atmospheric pollution is increasing. Hence, the power utilities are forced to limit their emissions within the prescribed limits. Therefore, the minimization of fuel cost as well as exhaust gas emissions is becoming an important and challenging task in the short-term scheduling of hydro-thermal energy systems. This paper proposes a novel algorithm known as WCA-ER (Water Cycle Algorithm with Evaporation Rate) to inspect the short term EEPSHES (Economic Emission Power Scheduling of Hydro-thermal Energy Systems). WCA has its ancestries from the natural hydrologic cycle i.e. the raining process forms streams and these streams start flowing towards the rivers which finally flow towards the sea. The worth of WCA-ER has been tested on the standard economic emission power scheduling of hydrothermal energy test system consisting of four hydropower and three thermal plants. The problem has been investigated for the three case studies (i) ECS (Economic Cost Scheduling), (ii) ES (Economic Emission Scheduling) and (iii) ECES (Economic Cost & Emission Scheduling). The results obtained show that WCA-ER is superior to many other methods in the literature in bringing lower fuel cost and emissions.

Key Words: **Economic Emission Scheduling, Multi-objective Optimization, Water Cycle Algorithm, Evaporation Rate, Fuel Emissions, Exhaust Gas Emissions**

1. INTRODUCTION

The problem of economic power scheduling of all thermal plants [1,2] and EPSHES (Economic Power Scheduling of Hydrothermal Energy Systems) has been solved for last many years due to the huge importance. The EPSHES is basically to determine the optimal amount of water for the hydropower plants and the power output from the thermal plants in a specified horizon so as to minimize the total cost of electrical energy. The solution of EPSHES involves many constraints of the hydropower and thermal plants including cascade nature of hydropower plants, varying reservoir inflows, limits of the reservoir storage, limits on the discharge capacity, water transport delay, the prohibited discharge zones of

* Department Electrical Engineering, University of Engineering & Technology, Taxila.

hydropower plants, multiple valve point effects on thermal fuel cost curves, ramp rates of thermal plants, the varying load demand, and the limitations on the generation by the hydropower and thermal plants[3]. The problem of EPSHES reduces to only minimize the fuel cost of thermal plants as the generation cost of hydropower plants is insignificant. But due to the implementation of clean energy act and zero emission regulations, the problem of EPSHES has been transformed into EEPSHES, which includes the minimization of exhaust gas emissions in addition to the minimization of total fuel cost. The problem of short term EEPSHES is the most vital problem in the power system operation which controls the total production cost by deciding the share of thermal energy due to the unavailability of hydropower at a specified interval of time. This thermal energy is also responsible for the exhaust gas emissions making the EEPSHES as multi-objective optimization problem which is more complex and complicated to solve as compared to a single objective optimization problem of EPSHES. Therefore, both the problems of minimizing fuel cost and fuel emissions are solved simultaneously in EEPSHES using three case studies (i) ECS (ii) EES and (iii) ECES. As both these objectives are of contradictory nature to each other, hence a cost penalty method has been proposed to find a trade-off between these two contradictory objectives.

In the developed countries, due to the vitality of the environmental concerns, EEPSHES problem is being extensively investigated and it is under active research due to stronger needs of economical operating schedules.

Several methods have been proposed and discussed in [4] to reduce the exhaust gas emission levels of thermal plants. These exhaust gas emissions may be taken as an objective function in economic dispatch problem. Besides them various other techniques such as Fuzzy Satisfaction Decision Approach [5], Improved Back-Propagation Neural Network [6], Maximizing Decision Recursive Technique [7], Multi-objective Approach using Evolutionary Algorithm [8], Improved GA (Genetic Algorithm) [9,10], PSO (Particle Swarm Optimization) [11,12], DE (Differential Evolution) [13,14] and Gravitational Search Algorithm [15,16] have been previously applied to reduce the emissions.

In this paper an improved form of WCA, known as WCA-ER presented by Sadollah, et. al. [17] has been used to solve the non-linear and non-convex EEPSHES problem. This algorithm has its ancestries from the water cycle process of the nature that how the rain process forms streams and these streams flow towards rivers and then these rivers finally drops into sea. The performance of WCA-ER was compared with GA, PSO and DE for several bench mark constrained optimization problems and WCA-ER was found out to be superior than these [17]. The WCA-ER has not yet been investigated to solve the problem of power system operation. In the proposed work, short-term hydrothermal scheduling problem has been investigated using WCA-ER while taking into account the non-convexity of thermal plants' fuel cost characteristics that arise due to valve point effect. The effectiveness of WCA-ER has been tested on a standard test system of EEPSHES problem for different cases.

The contribution of the proposed work is, the highly non-convex and complex problem of EEPSHES has completely been modelled for the environment of WCA-ER and a complete algorithm has been developed whose parameters have effectively been tuned so as to achieve the optimum results for all the three cases of ECS, EES and ECES. The comparison of the results with other strong techniques shows that WCA-ER has been successful in finding lower fuel costs and lesser exhaust gas emissions in all the three cases.

2. MATHEMATICAL FORMULATION OF EEPSHES PROBLEM

Mathematically, the objective function and constraints for EEPSHES problem are formulated as follows:

2.1 Economic Cost Scheduling

The objective of pure ECS (Economic Fuel Cost Scheduling) problem is the minimization of total fuel cost of thermal plants. Mathematically it is represented as [3]:

$$\text{minimize } F = \sum_{t=1}^{M}\sum_{x=1}^{N_s} f_x\left(PG_{sxt}\right) \tag{1}$$

where, F is the total fuel cost, f_x is the fuel cost of xth thermal plant, PG_{sxt} is the power generation of xth thermal generating unit at time t,M are the total number of time intervals for the scheduled period and N_s are the total number of thermal plants.

The objective function of both convex and non-convex nature will be handled in this research work:

2.1.1 Convex Objective Function

Conventionally, the fuel cost function of thermal plants can be represented as a quadratic function as follows:

$$f_x\left(PG_{sxt}\right) = a_x PG_{sxt}^2 + b_x PG_{sxt} + c_x \tag{2}$$

where, a_x, b_x, c_x are the fuel cost coefficients of xth thermal plant.

2.1.2 Non-Convex Objective Function

For the precise and real-world modeling of problem, the above mentioned fuel cost function needs to be reviewed. The real-world characteristics involve valve point effect and the objective function is re-written as:

$$f_x\left(PG_{sxt}\right) = a_x PG_{sxt}^2 + b_x PG_{sxt} + c_x + \left|d_x * \sin\left\{g_x\left(PG_{sx}^{min} - PG_{sxt}\right)\right\}\right| \tag{3}$$

where, d_x, g_x are the fuel cost coefficients of xth thermal plant showing valve point effect.

2.2 Economic Emission Scheduling

The EES problem is to minimize the amount of exhaust gas emissions from thermal plants due to burning of fossil fuels used for generation of electricity. The emission released by thermal plant can be formulated as summation of an exponential function with a quadratic one [8]. The EES problem is written mathematically as:

$$\text{minimize } E = \sum_{t=1}^{M}\sum_{x=1}^{N_s} e_{xt}\left(PG_{sxt}\right) \tag{4}$$

where, E is the total fuel emissions, and e_{xt} are the total amount of exhaust gases released by xth thermal plant.

$$e_{xt}\left(PG_{sxt}\right) = \alpha_{sx} PG_{sxt}^2 + \beta_{sx} PG_{sxt} + \gamma_{sx} + \eta_{sx}\exp\left(\rho_{sx} PG_{sxt}\right) \tag{5}$$

where, α_x, β_x, γ_x, η_x, ρ_x are the emission coefficients of xth thermal plant.

2.3 Economic Cost and Emission Scheduling

The mutual ECES problem seeks a trade-off relation between exhaust gas emissions and fuel cost. Emission scheduling is incorporated in pure economic dispatch problem by adding emission cost in conventional cost scheduling. This becomes a multi-objective ECES problem, converted into a single one by introducing a cost penalty approach as follows [6]:

$$\text{Min TC} = \sum_{t=1}^{M}\sum_{x=1}^{N_s}\left[f_{xt}\left(PG_{sxt}\right) + CPF_t * e_{xt}\left(PG_{sxt}\right)\right] \tag{6}$$

The trade-off relation between fuel cost and exhaust gas emission is developed as:

$$\text{Min TC} = \sum_{t=1}^{M}\sum_{x=1}^{N_s}\left[K_{xt} * f_{xt}\left(PG_{sxt}\right) + K_2 * CPF_t * e_{xt}\left(PG_{sxt}\right)\right] \tag{7}$$

where, CPF_t cost penalty factor at time interval *t* and K_1, K_2 are the weight factors.

The route of finding the cost penalty factors is given below:

(i) Compute the average production cost and average exhaust gas emission of each generating plant at its maximum rated power.

(ii) Obtain the ratio h_{sx} by dividing the computed average production cost with the average emission according to following equation. The numerator and the denominator of the Equation (8) are the formulae for calculating the average production cost and the average exhaust gas emissions respectively.

$$h_{sx}\left(\frac{\$}{lb}\right)=\frac{F\left(PG_{sx}^{\max}/PG_{sx}^{\max}\right)}{E\left(PG_{sx}^{\max}/PG_{sx}^{\max}\right)} \tag{8}$$

(iii) Re-arrange the computed values of h_{sx} in an ascending order.

(iv) Starting from the smallest h_{sx} add max loading limit of each generating unit one at a time until $\Sigma PG_{sx}^{max} \geq PD_t$ is achieved.

(v) At this phase, h_{sx} related with last unit is the cost penalty factor CPF_t for a given power demand at time t.

From above procedure it is obvious that the value of cost penalty factor CPF_t depends on the power demand during each interval t and it varies according to power demand.

2.4 Constraints

The above described objective functions are to be minimized subject to various hydraulic and thermal constraints [3], which can be written mathematically as:

2.4.1 Power Balance Constraint

The total hydropower and thermal generations at each time interval t should meet the forecasted load demand.

$$\sum_{y=1}^{N_h} PG_{hyt} + \sum_{x=1}^{N_s} PG_{sxt} = PD_t \tag{9}$$

where, PG_{hyt} is the generated power of yth hydropower unit at interval t, PD_t is the power demand at interval t and N_h is the total number of hydropower plants

The power generated by the hydropower plant involves the storage volume of reservoir and discharge rate of water and it is expressed as:

$$PG_{hyt}=A_{1y}U_{hyt}^2+A_{2y}U_{hyt}^2+A_{3y}U_{hyt}D_{hyt}+A_{4y}U_{hyt}+A_{5j}D_{hyt}+A_{6y} \tag{10}$$

where, A_{1y}, A_{2y}, A_{3y}, A_{4y}, A_{5y}, A_{6y} are the generation coefficients of yth hydropower plant, U_{hyt} is the reservoir storage volume of yth plant at time t and D_{hyt} is the water release of yth plant at time t.

2.4.2 Generation Capacity Constraint

$$PG_{sx}^{\min} < PG_{sxt} < PG_{sx}^{\max} \tag{11}$$

$$PG_{hy}^{\min} < PG_{hyt} < PG_{hy}^{\max} \tag{12}$$

where, PG_{sx}^{min}, PG_{sx}^{max} are the minimum & maximum generating capacity of xth thermal plant and PG_{hy}^{min}, PG_{sy}^{max} are the minimum & maximum generation capacity of yth hydropower plant.

2.4.3 Discharge Rate Limit

$$D_{hy}^{\min} < D_{hyt} < D_{hy}^{\max} \tag{13}$$

where, D_{hy}^{min}, D_{hy}^{max} are the minimum and maximum discharge limits of yth reservoir.

2.4.4 Reservoir Volume Storage Constraint

$$U_{hy}^{min} < U_{hy} < U_{hy}^{max} \tag{14}$$

where, U_{hy}^{min}, U_{hy}^{max} are the minimum & maximum reservoir storage limits of yth reservoir.

2.4.5 Water Balance Constraint

$$U_{hyt} = U_{hy,t-1} + \ln F_{hyt} - D_{hyt} - S_{hyt} + \sum_{n=1}^{R_{uy}} \left(D_{hn,t-\tau_{ny}} + S_{hn,t-\tau_{ny}} \right) \tag{15}$$

where, $\ln f_{hyt}$ is the natural inflow of yth hydropower plant respectively at time t, S_{hyt} is the spillage discharge rate of yth hydropower plant respectively at time t, R_{uy} is the number of upstream hydropower generating units immediately above the yth reservoir and τ_{ny} is the water transport time delay from reservoir n to reservoir y.

2.4.6 Reservoir End Conditions

$$U_y^0 = U_y^{Ini}, U_y^M = U_y^{End}; y = 1,2,.....N_h \tag{16}$$

where, U_y^{Ini}, U_y^{End} are the initial & final reservoir volume storage restrictions of yth reservoir.

The Equations (11-16) are the constraints. The constraints need to be satisfied for all the variables. After each step; initialization of variables and calculation of other variables, these constraints are repeatedly checked and satisfied. These equations are used to confirm whether the initialized variables and the calculated variables are within their prescribed limits. All these variables must satisfy these constraints mentioned in Equations (11-16).

3. WATER CYCLE ALGORITHM WITH EVAPORATION RATE

3.1 Basic Concept

WCA-ER mimics the natural water cycle as formation of streams from rain and then their flow towards rivers and then flow of these rivers towards the sea. The first step is the assumption of rain so that a population of streams is generated randomly.

3.2 Initialization

A population of design variables i.e. the population of streams is initially generated randomly. The individual having the best fitness value i.e. the best stream is chosen as sea and some next as rivers. The remaining streams flow towards rivers and sea [17]. Initially N_{pop} streams are created. Each stream created is a candidate solution. The total population of stream as mentioned in [17] is:

$$\text{Total Population} = \begin{bmatrix} \text{Sea} \\ \text{River}_1 \\ \text{River}_2 \\ \vdots \\ \text{Stream}_{Nsr+1} \\ \text{Stream}_{Nsr+2} \\ \vdots \\ \text{Stream}_{Npop} \end{bmatrix} = \begin{bmatrix} z_1^1 & z_2^1 & z_3^1 & \cdots & z_{Nvar}^1 \\ z_1^2 & z_2^2 & z_3^2 & \cdots & z_{Nvar}^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ z_1^{Npop} & z_2^{Npop} & z_3^{Npop} & \cdots & z_{Nvar}^{Npop} \end{bmatrix} \tag{17}$$

The stream having the lowermost value is marked as the sea. N_{sr} (a predefined parameter) is the sum of a sea and total of number of rivers as per Equation (18). The remaining number of streams N_{stream} might start flowing towards the rivers or directly towards the sea will be calculated as per Equation (19) as follows:

$$N_{sr} = \text{Number of Rivers} + 1 \text{ (Sea)} \tag{18}$$

$$N_{stream} = N_{pop} - N_{sr} \tag{19}$$

The sea absorbs the water from river and every river absorbs the water from the streams. Some streams will might directly flow towards the sea as well. The intensity of flow of streams determines the amount of water entering a specific river or sea depends. The number of streams entering the sea and the no. of streams entering the river are calculated using the Equation (20).

$$NS_n = \text{round}\left\{\left|\frac{CV_n}{\sum_{x=1}^{N_{sr}} CV_x}\right| \times N_{stream}\right\}, n = 1,2,3,....., N_{sr} \quad (20)$$

Where CV_n is the fitness value or the cost function. The absolute sign is used to eliminate the negative sign and round operator is used because any value other than positive integers cannot be assigned to a river or sea. e.g. 1.5 or 1.7 streams flow to the river.

3.3 Movement of Streams to the Rivers or Sea

Fig. 1 [17] but modified& redrawn) shows a stream flowing towards a specific river. The connection lines are also shown. The distance Z between the river and the stream is updated as:

$$Z \in (0, C \text{ x dist}), C>1 \quad (21)$$

The value of C is such that, $1 \leq C \leq 2$, and the finest value for C may be 2; is the distance between stream and river. Keeping C > 1 bounds streams to flow in various directions towards rivers. Same concept is also used to indicate rivers flowing towards the sea [17]. The latest positions of streams, rivers and sea are given using the following equations:

$$Z^{i+1}_{stream} = Z^{i}_{stream} + rnd \times C \times \left(Z^{i}_{River} - Z^{i}_{stream}\right) \quad (22)$$

$$Z^{i+1}_{stream} = Z^{i}_{stream} + rnd \times C \times \left(Z^{i}_{sea} - Z^{i}_{stream}\right) \quad (23)$$

$$Z^{i+1}_{River} = Z^{i}_{River} + rnd \times C \times \left(Z^{i}_{sea} - Z^{i}_{River}\right) \quad (24)$$

where, rnd is a uniformly distributed random number between 0 and 1. Equation (22) depicts streams flowing towards the corresponding river and Equation (23) depicts streams flowing directly towards the sea. If the fitness of the streams comes out to be better than its connecting rivers then the streams and river is swapped with each other. The same is done for the river and sea.

3.4 Evaporation and Raining Process

In the evaporation process sea water vaporizes as the streams or rivers flow towards the sea. This results in rainfall to form new streams. It is therefore checked if the rivers or streams have advanced up to the sea to make the evaporation process occur [17]. This avoids premature convergence of this algorithm. The following condition is used to check this evaporation condition:

$$\text{Case 1} \ \left\|Z^{x}_{sea} - Z^{x}_{River} - 1\right\| < dist_{max} \text{ or } rnd < 0.1, x = 1,2,3,.....N_{sr} - 1$$

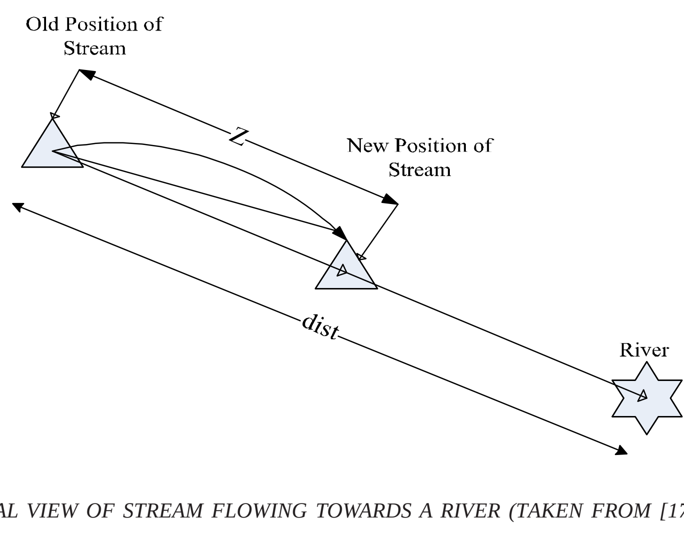

FIG. 1. GRAPHICAL VIEW OF STREAM FLOWING TOWARDS A RIVER (TAKEN FROM [17] AND RE-DRAWN)

if the above condition in Case 1 becomes true then start the raining process as per Equation (25), where $dist_{max}$ is a small number (very near to zero).

$$Z_{stream}^{new} = \text{Min Lim} + rnd \times (\text{Max Lim} - \text{Min Lim}) \quad (25)$$

The same condition of evaporation is checked for those streams which start flowing directly to the sea. The condition for evaporation for the streams directly flowing towards the sea is:

$$\text{Case 2} \ \left\| Z_{sea}^{x} - Z_{Stream}^{x} - 1 \right\| < dist_{max}, x = 1,2,3,.....NS_1$$

If the above condition in Case 2 becomes true, then start the raining process as per Equation (26):

$$Z_{stream}^{new} = Z_{sea} + \sqrt{\sigma} \times rndn(1, N) \quad (26)$$

where, σ depicts the area being searched around the sea. After the evaporation the created streams with σ variance are disseminated around the sea. rndn(1,N) is a vector of N standard Gaussian numbers. The smaller σ helps to search in minor region near the sea. The optimized value of σ is found to be 0.1 [17].

The value of $dist_{max}$ is calculated from Equation (27) and is decreasing adaptively. If a higher value of $dist_{max}$ is selected it avoids extra searches and its smaller value intensify the search closer to the sea.

$$dist_{max}^{i+1} = dist_{max}^{i} - \frac{dist_{max}^{i}}{\text{Max Itration}} \quad (27)$$

This raining process is analogous to mutation in GA.

The streams and rivers which have low flow intensity and are not able to reach the sea will definitely evaporate after some time. The evaporation process in WCA-ER is altered slightly by adding the concept of evaporation rate[17]. Therefore, the evaporation rate (ε) is defined as:

$$\varepsilon = \left\{ \frac{\sum_{n=2}^{N_{sr}} NS_n}{N_{sr} - 1} \right\} \times rnd \quad (28)$$

The Equation (28) clearly depicts a lower value of for the solutions having better fitness values and a relatively higher value of ε for the solutions having poor fitness values. Meaning, that the rivers having more number of streams have lower probability to evaporate compared to those having lesser number of streams. Therefore, one more evaporation condition for those rivers having fewer streams has to be satisfied to perform the raining process again. These conditions are:

$$\text{Case 3} \exp\left(\frac{-\text{Iteration No}}{\text{MaxIteration}} \right) < rnd \text{ and } NS_x < \varepsilon$$

If the above conditions in Case 3 are satisfied, then the raining process is started again using Equation (25). If the evaporation condition is satisfied for any river, then that specific river along with its streams will be removed and new streams and a river will be created but in a different position.

4. IMPLEMENTATION OF WCA-ER FOR THE SOLUTION OF EEPSHES

4.1 Initialization

The structure of solution for the hydro-thermal scheduling problem consists of two control variables; the discharge of water for hydropower plants and power generation by thermal plants. Both the variables are initialized within their prescribed limits as:

$$D_{hyt} = D_{hy}^{min} + rnd \times \left(D_{hy}^{max} - D_{hy}^{min} \right) \quad (29)$$

$$PG_{sxt} = PG_{sx}^{min} + rnd \times \left(PG_{sx}^{max} - D_{sx}^{min} \right) \quad (30)$$

where, rnd is the random number generated in (0,1). A candidate population of streams will be initialized as:

$$X_{kt} = \begin{pmatrix} D^1_{h1} & D^1_{h2} & D^1_{hj} & D^1_{hN_n}; & PG^1_{s1} & PG^1_{s2} & PG^1_{si} & PG^1_{sN_s} \\ D^2_{h1} & D^2_{h2} & D^2_{hj} & D^2_{hN_n}; & PG^2_{s1} & PG^2_{s2} & PG^2_{si} & PG^2_{sN_s} \\ D^t_{h1} & D^t_{h2} & D^t_{hj} & D^t_{hN_n}; & PG^t_{s1} & PG^t_{s2} & PG^t_{s2} & PG^t_{sN_s} \\ D^M_{h1} & D^M_{h2} & D^M_{hj} & D^M_{hN_n}; & PG^M_{s1} & PG^M_{s2} & PG^M_{s2} & PG^M_{sN_s} \end{pmatrix} \quad (31)$$

where, X_k is the kth stream or candidate solution.

4.2 Constraint Handling

Hydrothermal scheduling problem is more convoluted due to the involvement of many equality and inequality constraints. And, the fulfillment of all these constraints is very important and tedious task in this problem. In the proposed technique, pragmatic set of rules have been developed to fulfill these constraints.

4.2.1 Constraint Handling for Inequality Constraints

New streams are created after the raining process, which may violate the limits. If any stream candidate violates its limits, then the Equation (32) is used to clamp it.

$$PG_{sxt} = \begin{cases} PG^{min}_{sx} \text{ if } PG_{sxt} < PG^{min}_{sx} \\ PG^{max}_{sx} \text{ if } PG_{sxt} < PG^{max}_{sx} \end{cases}$$
$$D_{hyt} = \begin{cases} D^{min}_{hy} \text{ if } D_{hyt} < D^{min}_{hy} \\ D^{max}_{hy} \text{ if } D_{hyt} < D^{max}_{hy} \end{cases} \quad (32)$$

4.2.2 Constraint Handling for Equality Constraints

The equality constraints are more convoluted to be handled problem. The water balance constraint and power balance constraint are required to be handled after the initialization and every time whenever the raining process starts. A pragmatic method to balance these constraints is devised as follows:

4.2.2.1 Water Balance Constraint Handling

To meet exactly the limits on reservoir storage as per Equation (10) the water discharge rate of the yth hydro plant D_{hyj} in the dependent interval j is then calculated by:

$$D_{hyj} = U_{hyO} - U_{hyM} - \sum_{\substack{t=1 \\ t\neq 1}}^{M} D_{hyt} - \sum_{t=1}^{M}\sum_{m=1}^{R_{uj}} \left(D_{hm,t-\tau my}\right) + \sum_{t=1}^{M} \ln F_{hyt} \quad (33)$$

If the discharge violates the constraint, then it is attuned according to Equation (33) and another random interval is selected. The practice reiterates until the discharge fulfills the constraint.

4.2.2.2 Power Balance Constraint Handling

To fulfill the power balance constraint exactly as per Equation (4), the dependent thermal unit j from the thermal plants is randomly selected and dependent thermal generation $PG^t_{s,j}$ is calculated using the following Equation (34):

$$PG^t_{s,j} = PD^t - \sum_{y=1}^{N_h} PG^t_{h,y} - \sum_{\substack{i=1 \\ i\neq j}}^{N_s} PG^t_{s,i} \quad (34)$$

The Equation (34) step is reiterated if the dependent thermal power generation does not fulfill the inequality constraint described in Equation (6). The dependent thermal unit is not selected again while selecting a new random thermal unit.

4.3 Flowchart of Proposed WCA-ER for EEPSHES Problem

The detailed flowchart of the proposed WCA-ER for EEPSHES problem is shown in **Fig. (2).**

5. SIMULATION RESULTS

The EEPSHES problem has been mapped as per proposed WCA-ER algorithm in Microsoft Visual C++ 6.0

Environment runs on a Dual Core 1.2GHz Personal Computer. The efficacy of proposed algorithm is validated through its successful application on illustrative hydrothermal test system involving four cascaded hydropower plants and three thermal plants with non-linear and non-smooth characteristics. The scheduling horizon is taken as 24 hour with 1 hour time interval. The time delay effect of hydropower reservoirs and valve-point effect of thermal plants is also considered in this system. The hydropower sub-system configuration, hydropower unit generating coefficients, water discharge limits, reservoir volume limits, reservoir inflows, hourly power demand, generation limits and thermal machine fuel cost and emission coefficients were taken from [18].It can be seen from all the references given and many other available in the literature that this is a standard hydrothermal emission scheduling test system which is being used by all the researchers. The detail such as nature of the fuel and type of the plant used is not available in the literature. However, it is stated that as this system is

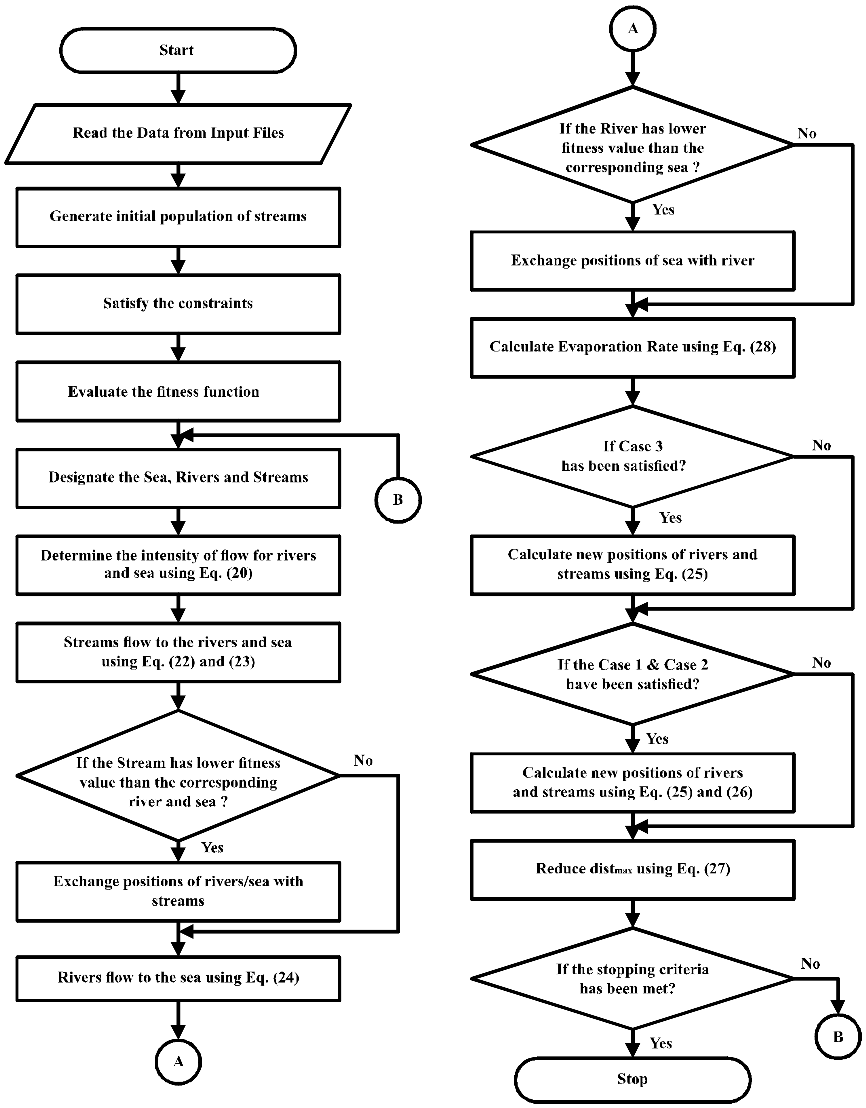

FIG. 2. FLOWCHART OF THE PROPOSED WCA-ER FOR EEPSHES

to investigate the hydrothermal scheduling problem with reference to environment so it may be concluded that these fuel cost curves and fuel emission curves have been derived for the non-environment friendly fuels which may be coal, oil or gas. These exhaust gas emissions contain all of the SO_x (Sulfur Oxides), NO_x (Nitrogen Oxides) and CO_2 (Carbon Dioxide).

The evolutionary model for control parameters of WCA-ER is shown in **Table 1**. This system has been solved for following three cases: (i) ECS, (ii) EES (iii) ECES.

5.1 Case Study-1 (Economic Cost Scheduling)

In this case the only fuel cost objective as per Equation (7) is considered. Here the objective is to only curtail the fuel cost of thermal plants. The value of weight factors in this case will be $K_1 = 1$, $K_2 = 0$. For satisfaction of active power balance constraint, the priority list of thermal plants is same over the whole scheduling horizon in this case. **Table 2** shows the optimal discharges of hydropower plants. **Table 3** shows the hourly optimal hydropower and thermal power schedules obtained from proposed WCA-ER method.

TABLE 1. EVOLUTIONARY MODEL OF WCA-ER FOR EEPSHES

Test System	Npop	Nsr	distmax	Iteration Count
ECS	200	16	0.01	500
EES	200	16	0.01	500
ECES	200	16	0.01	500

TABLE 2. OPTIMAL HYDROPOWER DISCHARGES ($X10^4M^3$) FOR ECS

Hour	Dh1	Dh2	Dh3	Dh4
1	6.1046	8.1792	29.6402	9.1269
2	5.4318	6.1949	29.9045	6.3594
3	5.9362	6.7230	30.0000	6.2664
4	8.9485	7.4538	29.9646	8.3694
5	8.4847	6.5939	13.2366	6.0991
6	11.0949	7.2175	28.3448	8.8944
7	12.7148	10.2435	26.2268	11.3994
8	6.5577	7.6731	14.6733	9.3565
9	7.6597	10.6396	15.6895	14.0828
10	8.1283	11.7518	11.7939	11.0585
11	7.4684	7.3311	14.3385	14.7082
12	6.6907	11.6322	14.7312	18.3573
13	7.6446	6.4461	14.7778	15.4409
14	5.4657	7.5652	10.8462	17.4978
15	9.8851	9.1026	12.8334	19.8362
16	8.6102	7.6774	17.0467	19.3362
17	6.4993	8.0413	13.1449	19.9229
18	5.7685	7.7920	10.6561	19.4905
19	10.2888	8.9853	13.4212	19.9049
20	8.1666	8.5522	11.1023	19.5773
21	6.3243	6.4746	10.1603	16.5704
22	10.9906	7.1757	15.4951	18.2782
23	6.6369	9.2974	10.8587	19.8235
24	13.4993	13.2565	10.5476	19.4153

5.2 Case Study-2 (Economic Emission Scheduling)

In this case the objective is to only curtail the exhaust gas emission of thermal plants. So, the value of weight factors will be $K_1 = 0$, $K_2 = 1/CPF_t$. In this case the priority sequence of thermal plants is also same for whole scheduled period for the satisfaction of active power balance constraint. **Table 4** shows the optimal discharges of hydropower plants. **Table 5** shows the hourly optimal hydropower and thermal power schedules obtained from proposed WCA-ER method.

TABLE 3. OPTIMAL POWER DISPATCH SCHEDULE (MW) FOR ECS

Hour	PGh1	PGh2	PGh3	PGh4	PGs1	PGs2	PGs3	PD
1	62.5916	62.9360	0.0000	164.8901	109.0528	211.0222	139.5074	750
2	57.6515	51.3260	0.0000	127.2092	20.0000	296.2949	227.5183	780
3	62.2573	56.2608	0.0000	121.4932	105.7809	214.0372	140.1707	700
4	82.9467	61.9031	0.0000	138.4805	20.0000	296.6697	50.0000	650
5	79.5589	57.0285	35.3947	133.4103	20.0000	294.6076	50.0000	670
6	90.9213	61.0607	0.0000	187.4464	24.9484	295.3230	140.3003	800
7	93.6945	75.2684	0.0000	232.0191	106.2708	213.1185	229.6286	950
8	64.8552	61.0859	28.0119	221.5919	104.0478	210.7085	319.6987	1010
9	73.2386	74.8742	28.1228	275.8178	107.0819	212.0705	318.7942	1090
10	77.0507	77.3766	36.5121	252.9144	20.0000	297.2368	318.9095	1080
11	73.7672	56.6824	34.8186	301.4146	20.0000	296.9785	316.3387	1100
12	68.6662	75.5455	36.7244	333.0647	21.5489	295.4081	319.0421	1150
13	76.2520	49.6066	40.1356	306.8277	20.0000	298.7931	318.3850	1110
14	59.3883	57.7272	44.6915	322.0130	20.0001	297.2280	228.9519	1030
15	91.4095	66.3617	47.9707	335.8885	106.7111	213.3353	148.3232	1010
16	84.0363	58.5501	39.6388	328.5988	106.8735	212.9762	229.3262	1060
17	68.5625	60.0439	48.8339	328.2519	20.0001	297.8831	226.4246	1050
18	62.2417	57.4056	50.8222	317.6560	20.0000	297.0922	314.7824	1120
19	93.9813	62.7142	51.9487	313.6660	20.4656	297.9737	229.2506	1070
20	80.9972	60.0253	52.6079	309.1548	105.1973	212.6637	229.3537	1050
21	66.9973	49.0437	53.6533	284.2017	20.0000	298.4888	137.6153	910
22	96.5056	54.7913	54.4432	289.6595	20.0000	294.6003	50.0000	860
23	69.5485	66.0263	56.2835	292.6704	20.0000	295.4713	50.0000	850
24	104.5733	77.3356	56.9995	281.1480	20.0000	209.9435	50.0000	800
Total Fuel Cost							$ 40,906.20	
Total Fuel Emission							26,060.02lb	

5.3 Case Study-3 (Economic Cost & Emission Scheduling)

In this case an amalgamated objective function with attempt to optimize both fuel cost and exhaust gas emission is engaged. The value of weight factors for this case is $K_1 = 1$, $K_2 = 1$. The optimal hydropower discharges and optimal hourly dispatch schedules of hydropower and thermal plants for this case study are presented in **Tables 6-7** respectively.

TABLE 4. OPTIMAL HYDROPOWER DISCHARGES ($X10^4M^4$) FOR EES

Hour	Dh1	Dh2	Dh3	Dh4
1	8.2892	7.1573	30.0000	6.1427
2	6.1844	7.5938	29.9964	6.1544
3	9.5081	6.1081	29.9820	6.0450
4	5.9062	6.2439	29.9629	6.0717
5	7.8051	6.7318	29.9703	6.0741
6	8.9871	6.2913	29.9922	8.0334
7	11.8804	8.0337	29.7577	11.5543
8	9.7033	8.1483	13.4735	13.3032
9	8.2713	10.7655	14.8042	14.6578
10	8.3964	6.8008	11.1870	15.8722
11	8.9473	7.4121	15.9622	17.6727
12	9.3741	11.3317	12.8390	19.9830
13	11.8918	7.9828	11.4521	16.7531
14	8.3741	7.7955	12.6205	17.0243
15	7.4581	7.5702	14.2190	17.1806
16	10.5005	7.5293	12.7237	18.1009
17	5.8814	11.5377	10.9849	19.6596
18	9.6708	10.9204	11.3354	19.8057
19	5.4946	11.2345	10.6427	19.9033
20	7.9418	9.5109	10.6822	19.4710
21	6.4736	10.1611	11.3976	20.0000
22	6.2181	9.7637	10.5932	19.9931
23	6.6165	7.0792	11.7861	19.9881
24	5.2260	8.2962	15.9536	19.9438

The fuel cost and exhaust gas emissions for the above three studies have been collectively summarized in **Table 8**. In Table 8, the second and third column are of ECS, in which the objective function is to minimize only the fuel cost without considering fuel emissions. However, fuel emissions are written against the fuel costs. In this case, the minimum generation cost is achieved by WCA-ER but the amount of exhaust gas emission is higher than EES and ECES because emissions are not considered here, while they are just written against the fuel cost.

TABLE 5. OPTIMAL POWER DISPATCH SCHEDULE (MW) FOR EES

Hour	PGh1	PGh2	PGh3	PGh4	PGs1	PGs2	PGs3	PD
1	77.4165	57.3241	0.0000	130.8086	169.6770	204.3197	110.4541	750
2	63.3586	60.3145	0.0000	127.5194	175.0000	263.1649	90.6425	780
3	84.6393	52.1450	0.0000	121.8944	170.6317	187.0569	83.6328	700
4	61.0339	54.6181	0.0000	116.3476	174.9603	167.2592	75.7809	650
5	74.5366	58.6755	0.0000	138.3407	154.9486	177.6646	65.8341	670
6	81.0147	56.0022	0.0000	182.1817	174.9796	240.0116	65.8102	800
7	91.6290	66.2558	0.0000	239.0626	175.0000	293.3554	84.6972	950
8	83.0248	66.2805	19.1151	270.4206	175.0000	286.3440	109.8149	1010
9	75.9847	77.9235	18.7092	294.9102	175.0000	299.9667	147.5058	1090
10	77.5647	57.4739	27.3226	315.8865	174.8895	299.7609	127.1020	1080
11	81.6762	62.3506	20.3942	340.0158	174.9758	296.1606	124.4268	1100
12	84.1762	80.5469	30.8842	355.1892	174.9849	285.7449	138.4737	1150
13	94.3549	63.9588	35.3134	326.5635	174.9590	300.0000	114.8505	1110
14	79.2513	63.5360	37.8243	325.4940	173.3511	275.9804	74.5630	1030
15	74.0154	62.9649	40.9218	326.1293	174.9976	232.5274	98.4437	1010
16	91.3872	62.9736	44.5163	330.5286	174.9952	275.3578	80.2414	1060
17	62.2482	80.4255	46.4973	336.3676	174.9701	275.0770	74.4144	1050
18	87.7757	74.6755	49.3178	331.4999	175.0000	299.8722	101.8589	1120
19	58.9007	72.9324	49.8259	327.2611	174.8971	292.8554	93.3274	1070
20	77.4292	64.3356	52.7274	318.3589	174.9888	281.0945	81.0657	1050
21	66.8533	66.5272	54.9978	313.2516	142.0689	187.2672	79.0340	910
22	65.0695	64.1528	56.1513	304.5324	160.7682	140.4382	68.8877	860
23	68.5899	50.0538	58.3878	294.6336	157.9677	156.3675	63.9997	850
24	57.1230	57.0766	56.6192	284.0968	164.1044	130.9800	50.0000	800
Total Fuel Cost							$ 47,114.98	
Total Fuel Emission							16,342.68lb	

The next two columns in Table 8 are of EES, in which the objective function is to minimize the fuel emissions only without considering the fuel cost. It can be seen that, in EES the lowest fuel emissions are reported by the WCA-ER method as compared to other methods but the fuel cost is higher than ECS and ECES and are just written against the fuel emissions.

The last two columns of Table 8 are of ECES. In this case both the minimization of fuel cost and fuel emissions has been taken into account in the objective function. Even then the fuel costs and fuel emissions obtained by WCA-ER are found to be lowest. However, they are a bit higher than the independent cases ECS and EES indicating that cost is compromised when both conflicting objective

TABLE 6. OPTIMAL HYDROPOWER DISCHARGES ($X10^4M^4$) FOR ECES

Hour	Dh1	Dh2	Dh3	Dh4
1	11.8477	7.8645	29.8337	8.8081
2	9.7614	6.4216	29.9254	6.6301
3	7.3465	6.8108	29.5547	7.7086
4	5.0346	6.0861	29.9979	6.0000
5	5.0002	6.0197	29.7788	6.0039
6	6.6406	6.0787	27.5871	6.6368
7	9.4176	6.1248	13.7483	12.1122
8	6.3226	8.2604	28.8344	12.8459
9	8.9206	8.1707	29.5721	19.0626
10	5.5079	9.0175	13.0337	17.2788
11	8.7025	7.3063	10.5288	17.4190
12	11.5746	11.0684	10.8081	18.5341
13	9.8954	7.0877	11.0316	15.6308
14	9.7404	6.1881	10.5982	19.6879
15	5.8829	7.6665	13.9850	18.1857
16	8.8551	10.9819	10.9441	19.9846
17	11.0504	11.4869	10.2679	19.5272
18	12.7296	12.3343	13.1010	14.6610
19	5.7172	7.0117	10.0000	15.9939
20	8.4717	13.9244	10.4492	19.6782
21	7.0936	6.7326	10.7557	18.0715
22	8.3570	9.7133	10.5697	19.9892
23	6.0833	12.1771	10.1605	19.9915
24	5.0465	7.4661	13.7478	19.9384

functions; cost and emissions are taken into account in case of ECES.

The results of proposed WCA-ER method have been compared with the results obtained by PSO [19], IQPSO [20], DE [13], QADEVT [21] and SOHPSO_TVAC [22] in Table 8. The results clearly depict the superiority of WCA-ER over others in terms of reduction in both of the fuel cost and exhaust gas emission for all of the three cases.

TABLE 7. OPTIMAL POWER DISPATCH SCHEDULE (MW) FOR ECES

Hour	PGh1	PGh2	PGh3	PGh4	PGs1	PGs2	PGs3	PD
1	92.2835	61.2789	0.0000	161.5378	175.0000	209.8999	50.0000	750
2	83.9295	52.9503	0.0000	130.7568	175.0000	213.7197	123.6436	780
3	70.2721	56.8486	0.0000	138.1021	175.0000	209.7773	50.0000	700
4	52.8063	53.4541	0.0000	110.6720	175.0000	208.0676	50.0000	650
5	52.7099	54.0229	0.0000	133.2345	174.9997	205.0330	50.0000	670
6	66.1535	54.9245	0.0000	160.7973	174.9807	210.0118	133.1321	800
7	83.1620	55.1915	27.1130	241.7891	175.0000	230.5984	137.1461	950
8	64.0315	68.4376	0.0000	262.6696	175.0000	300.0000	139.8614	1010
9	81.7027	67.8134	0.0000	327.3859	174.9857	300.0000	138.1123	1090
10	58.5782	72.6016	14.0367	320.9319	175.0000	299.7596	139.0919	1080
11	82.6814	63.3734	20.1594	319.5060	175.0000	299.4337	139.8461	1100
12	96.1490	81.6052	22.5983	336.1228	174.9773	299.4256	139.1217	1150
13	89.1990	60.7897	27.7293	318.0563	175.0000	300.0000	139.2257	1110
14	88.9525	56.1060	32.6952	350.2104	175.0000	277.0036	50.0323	1030
15	62.9492	66.7138	34.9549	333.0080	174.9822	211.7535	125.6385	1010
16	85.1011	82.4932	39.9292	339.9034	174.9999	287.5732	50.0000	1060
17	96.1739	81.7800	40.8876	329.8001	174.9983	276.3602	50.0000	1050
18	100.7150	80.5682	42.9325	285.5166	174.9982	299.1425	136.1271	1120
19	61.1285	54.6581	46.4879	296.6213	174.9138	299.0319	137.1585	1070
20	81.2763	80.5664	50.9815	317.7929	174.9781	217.4038	127.0011	1050
21	71.8345	50.5211	53.5129	299.4736	174.9775	209.6805	50.0000	910
22	80.4593	66.9617	54.7225	305.4059	174.9806	127.4701	50.0000	860
23	64.2379	73.7756	56.1522	294.8998	175.0000	135.9346	50.0000	850
24	55.4564	52.2444	58.8921	284.0673	175.0000	124.3398	50.0000	800
Total Fuel Cost							$ 42,835.21	
Total Fuel Emission							16,755.60 lbb	

TABLE 8. SUMMARY OF RESULTS AND COMPARISON

Methods	ECS		EES		ECES	
	Fuel Cost ($)	Fuel Emission (lb)	Fuel Cost ($)	Fuel Emission (lb)	Fuel Cost ($)	uel Emission (lb)
Proposed WCA-ER	40,906.20	26,060.02	47,114.98	16,342.68	42,835.21	16,755.60
PSO [19]	42,474	28,132	48,263	16,928	43,280	17,899
IQPSO [20]	42,359	31,298	45,271	17,767	44,259	18,229
DE[13]	43,500	21,092	51,449	18,257	44,914	19,615
QADEVT[21]	42,587	30,786	46,100	17,535	43,395	18,234
SOHPSO_TVAC[22]	41,983	24,482	44,432	16,803	43,045	17,003

6. CONCLUSION

Short term EEPSHES is of significant importance in today's power system operation. In this paper, a new meta-heuristic naming WCA-ER has been applied to solve the multi-objective problem of short term EEPSHES. The combinatorial optimization problem of EEPSHES has been mapped according to the WCA-ER and all the constraints have been satisfied. The inequality and equality constraints have been handled by adopting some pragmatic rules. Then the efficacy of this technique has been investigated on a standard hydrothermal test system involving four cascaded hydropower plants and three thermal plants with three different cases. The simulation results reveal that the proposed technique has strength in solving optimally both fuel cost and exhaust gas emission scheduling. The cost obtained for ECS is lowest and the emissions obtained in EES are lowest but for the combined case of ECES, which is a multi-objective optimization problem of two conflicting objectives, a compromise between the fuel costs and fuel emissions has been obtained, which is also optimum as compared to other strong techniques in the literature. Therefore, the proposed WCA-ER algorithm is an effective method to find an optimal solution for the multi-objective EEPSHES problem.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the University of Engineering & Technology, Taxila, Pakistan, for providing support to carry out this research work.

REFERENCES

[1] Ahmad, A., and Asar, A. "A PSO Based Artificial Neural Network Approach for Short Term Unit Commitment Problem", Mehran University Research Journal of Engineering & Technology, Volume 29, pp. 607-20, Jamshoro, Pakistan, 2010.

[2] Malik, T., and Asar, A., "Neuro-Genetic Hybrid Approach for the Solution of Non-Convex Economic Dispatch Problem", Mehran University Research Journal of Engineering & Technology, Volume 28, pp. 289-302, Jamshoro, Pakistan, 2009.

[3] Malik, T.N., Zafar, S., and Haroon, S., "An Improved Chaotic Hybrid Differential Evolution for the Short-Term Hydrothermal Scheduling Problem Considering Practical Constraints", Frontiers of Information Technology & Electronic Engineering, Volume 16, pp. 404-17, 2015.

[4] Talaq, J.H., El-Hawary, F., and El-Hawary, M.E., "A Summary of Environmental/Economic Dispatch Algorithms", IEEE Transactions on Power Systems, Volume 9, pp. 1508-16, 1994.

[5] Huang, C.-M., Yang, H.-T., and Huang, C.-L. "Bi-Objective Power Dispatch using Fuzzy Satisfaction-Maximizing Decision Approach", IEEE Transactions on Power Systems, Volume 12, pp. 1715-21, 1997.

[6] Kulkarni, S.A., and Kothari, D.P., "Combined Economic and Emission Dispatch using Improved Backpropagation Neural Network", Electric Machines &Power Systems, Volume 28, pp. 31-44, 2000.

[7] Muralidharan, S., Srikrishna, K., and Subramanian, S. "Emission Constrained Economic Dispatch—A New Recursive Approach", Electric Power Components and Systems, Volume 34, pp. 343-53, 2006.

[8] Abido, M., "Environmental/Economic Power Dispatch using Multiobjective Evolutionary Algorithms", IEEE Transactions on Power Systems, Volume 18, pp. 1529-37, 2003.

[9] Chiang, C.-L. "Optimal Economic Emission Dispatch of Hydrothermal Power Systems", International Journal of Electrical Power & Energy Systems, Volume 29, pp. 462-69, 2007.

[10] Chiang, C.L., Liaw, J.H., and Su, C.T., "New Approach with a Genetic Algorithm Framework to Multi Objective Generation Dispatch Problems", European Transactions on Electrical Power, Volume 15, pp. 381-95, 2005.

[11] Wang, L., and Singh, C., "Reserve-Constrained Multiarea Environmental/Economic Dispatch Based on Particle Swarm Optimization with Local Search", Engineering Applications of Artificial Intelligence, Volume 22, pp. 298-307, 2009.

[12] Lu, S., Sun, C., and Lu, Z., "An Improved Quantum-Behaved Particle Swarm Optimization Method for Short-Term Combined Economic Emission Hydrothermal Scheduling", Energy Conversion and Management, Volume 51, pp. 561-71, 2010.

[13] Mandal, K., and Chakraborty, N., "Short-Term Combined Economic Emission Scheduling of Hydrothermal Power Systems with Cascaded Reservoirs using Differential Evolution", Energy Conversion and Management, Volume 50, pp. 97-104, 2009.

[14] Glotiæ, A., and Zamuda, A., "Short-Term Combined Economic and Emission Hydrothermal Optimization by Surrogate Differential Evolution", Applied Energy, Volume 141, pp. 42-56, 2015.

[15] Li, C., Zhou, J., Lu, P., and Wang, C., "Short-Term Economic Environmental Hydrothermal Scheduling using Improved Multi-Objective Gravitational Search Algorithm", Energy Conversion and Management, Volume 89, pp. 127-36, 2015.

[16] Tian, H., Yuan, X., Ji, B., and Chen, Z., "Multi-Objective Optimization of Short-Term Hydrothermal Scheduling using Non-Dominated Sorting Gravitational Search Algorithm with Chaotic Mutation", Energy Conversion and Management, Volume 81, pp. 504-19, 2014.

[17] Sadollah, A., Eskandar, H., Bahreininejad, A., and Kim, J.H., "Water Cycle Algorithm with Evaporation Rate for Solving Constrained and Unconstrained Optimization Problems", Applied Soft Computing, Volume 30, pp. 58-71, 2015.

[18] Basu, M., "An Interactive Fuzzy Satisfying Method Based on Evolutionary Programming Technique for Multiobjective Short-Term Hydrothermal Scheduling", Electric Power Systems Research, Volume 69, pp. 277-85, 2004.

[19] Mandal, K., and Chakraborty, N., "Short-Term Combined Economic Emission Scheduling of Hydrothermal Systems with Cascaded Reservoirs using Particle Swarm Optimization Technique", Applied Soft Computing, Volume 11, pp. 1295-302, 2011.

[20] Sun, C., and Lu, S., "Short-Term Combined Economic Emission Hydrothermal Scheduling using Improved Quantum-Behaved Particle Swarm Optimization", Expert Systems with Applications, Volume 37, pp. 4232-41, 2010.

[21] Lu, S., and Sun, C., "Quadratic Approximation Based Differential Evolution with Valuable Trade Off Approach for Bi-Objective Short-Term Hydrothermal Scheduling", Expert Systems with Applications, Volume 38, pp. 13950-60, 2011.

[22] Mandal, K.K., and Chakraborty, N., "Daily Combined Economic Emission Scheduling of Hydrothermal Systems with Cascaded Reservoirs using Self Organizing Hierarchical Particle Swarm Optimization Technique", Expert Systems with Applications, Volume 39, pp. 3438-45, 2012.