Multi Objective Multi Area Hydrothermal Environmental Economic Dispatch using Bat Algorithm

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Abstract—**This paper presents a Multi Objective, Multi Area Hydrothermal Environmental Economic Dispatch (MOMAHEED) problem which determines the optimal generating level of all the hydro and thermal generating units to adequately supply the demand, such that the total fuel cost of thermal plants in all areas and emissions are simultaneously curtailed while satisfying all physical and operational constraints. MOMAHEED is solved using Bat Algorithm (BA) which is inspired by echolocation behavior of micro bats. The multi objective function is converted to a single objective one using weighted sum method and cardinal priority ranking used to select the optimal solutions. The algorithm is tested on a four-area system considering three test cases and results in lower fuel costs as compared to Particle Swarm Optimization (PSO).**

Index Terms— **Bat Algorithm (BA), Multi Objective Multi Area Hydrothermal Environmental Economic Dispatch (MOMAHEED), Particle Swarm Optimization (PSO).**

I. Introduction

A Multi Area system is formed when multiple power system utilities in a state or in countries in distinct geographical locations are interconnected to form one big system via tie lines[1].

Around the world many neighbouring countries are entering into inter-utility electricity exchange agreements (power pool) in order to lower electricity production costs, improve security, make their networks more reliable and share their reserves. In order to reap these benefits of system interconnection, economic operation of the power plants is very critical.

Economic Dispatch (ED) which aims at minimizing cost of power production while satisfying the load demand is one of the most important aspects of power systems planning and operation which must be considered in a Multi Area Power System.

The main aim of Multi Area Hydrothermal Economic Dispatch (MAHED) is to satisfy the load demands of all areas by scheduling the power output of each committed generating unit among the hydroelectric and thermal plants while incorporating inter area power transactions in such a way that the thermal plants incur the least possible fuel cost while satisfying all operational and physical constraints of the hydrothermal plants and the power system in general[2].

The increasing public awareness of the environmental effects of power generation and the ratification of the Kyoto Protocol and the Paris Agreement by member states has forced utilities to modify their operational strategies to reduce pollution and atmospheric emissions like Nitrogen Oxides (NO_x), Carbon Dioxide (CO_2) and Sulphur Dioxide (SO_2) of the fossil fueled generating power plants[3]. As a result, the single objective MAHED problem is no longer sufficient in determining the economic operation of a Multi Area hydrothermal power system and therefore Multi Area Hydrothermal Environmental Economic Dispatch (MAHEED) problem is considered in this paper. MAHEED simultaneously curtails the total fuel cost of thermal plants and emissions while satisfying the load demand.

Motivation: As energy resources continue to dwindle, the cost of generating power is increasing and the demand is rising. This scenario becomes more complex with the increasing awareness of environmental pollution caused by fossil fueled power plants forcing utilities to modify their operation strategies to reduce the emissions. With the rising number of power pools, majority of which are built around hydrothermal systems, it is necessary to formulate and solve MAED problem while considering emissions and hydroelectric plants.

Paper Organization: The rest of this paper is organized as follows: Section II reviews previous works by various researchers, detailed MAHEED problem formulation is given in Section III, Section IV presents the proposed Methodology, Results Analysis and Discussions are done in Section V and then Conclusions are drawn in Section VI.

II. Review of Previous Works

This section reviews the works that have been done by researchers in solving MAED problem.

A. Multi Area Economic Dispatch (MAED)

MAED problem was formulated and solved for the first time in 1981 using Dantzig Wolfe decomposition principle[4] and then in 1995 using Network Flow Programming (NFP) [5]. MAED has been receiving a lot of attention in research since 2009 with over 100 publications to date as a result of the increasing number of power pools in the world. Various algorithms have since been proposed which include among others; Backtracking Search Algorithm (BSA)[6], Flower Pollination Algorithm[7], λ Concept and Tie line matrix [8], hybrid of Cockoo Search and Teaching Learning Based Algorithm[9], Real–Coded Genetic Algorithm (RCGA)[10] Differential Evolution[11], [12], PSO and its variants [1], [8], [11], Fuzzy Logic [14] and Direct (non-iterative) method [15].

B. Multi Area Hydrothermal Economic Dispatch (MAHED)

Two research works have considered hydro plants while solving MAED problem. In [16], an Optimality Condition Decomposition (OCD) technique along with parallel computation ability was used to solve Multi Area Dynamic Economic Dispatch (MADED) model for a retailer while taking into consideration hydro plants, wind plants and power pool market. Uncertainties of wind generation, electricity

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demand and electricity prices were modelled using Scenario Based Method (SBM) and OCD technique used to decompose MADED problem into several independent area based Dynamic Economic Dispatch (DED) problems which were then solved simultaneously using parallel computation ability. In [17], MADED problem was solved by decomposing the hydrothermal system into respective thermal and hydro sub problems which were then coordinated using Lagrange Multipliers. The hydro units were modelled as a set of cascaded hydro stations where water usage was coordinated over the entire study time using Network Flow Concept and Reduced Gradient method used to obtain an optimal solution by overcoming the linear characteristic of the Network Flow method

C. Multi Area Environmental Economic Dispatch (MAEED)

Pareto based Chemical Reaction Optimization Algorithm (PCRO) was proposed in [18] to solve the MAEED problem where a chemical molecule was used to represent each solution. Global search ability was enhanced by a kinetic energy based search procedure and a mechanism for self-adaptive neighborhood structure selection was embedded in the PCRO to increase the local search ability while still maintaining the population diversity. To enable the algorithm converge near a Pareto front, a grid based crowding distance strategy was introduced.
Dynamic Reserve Constrained MAEED problem was solved in [19] using a hybrid of Gradient Search Method and Improved Jaya Algorithm (IGJA). A mutation strategy consisting of mutation and crossover operators was embedded in the Jaya Algorithm to prevent the algorithm from converging prematurely and also to make the Pareto optimal solutions more accurate. The most preferable solution among the different Pareto optimal solutions was obtained using fuzzy decision making procedure.
A Multi Area, Multi Objective Dynamic Economic Dispatch (MAMODED) problem considering Renewable Energy (RE) sources (Solar and Wind) was solved using Modified Firefly Algorithm with Levy Flights and Derived Mutation (MFA-LF-DM) in [20] and in [21] while considering Multi Terminal DC Tie lines. Thermal and emission functions were modelled using cubic functions considering valve point effects and a weighting factor was used to convert the multi objective problem into a single objective one. Scenario Based Method (SBM) was used to model the uncertainty and variability of RE sources. The random movement of the objective function was then reduced using Levy Flights and exploration of the candidate solution improved by Derived Mutations.
Particle Swarm Optimization and its variants have also been used in [1],[22] and [23] to solve MAEED problem.

With the rising number of Multi Area systems as a result of increasing power pooling arrangements, a lot of research is being done in solving MAED problem. However, very little effort has been put towards solving MAED problem while considering emissions, and only two works have considered hydrothermal systems. MAED formulation which simultaneously takes into considerations emissions and hydrothermal systems has not been considered yet.

Contribution: MAED Problem for a hydrothermal system has been formulated and solved for the very first time while considering emissions. This formulation represents a practical power pool more accurately as most power pools are hydrothermal systems and emissions reductions in power generation is becoming more critical, thus the results obtained are realistic.

III. MAHEED FORMULATION

MAHEED problem is formulated as a multi objective optimization problem which simultaneously seeks to minimize fuel cost and emissions of thermal plants subject to the constraints of water availability (storage and inflow) of hydro plants, generator constraints, area power balance constraints as well as tie line limits.

A. Objective Functions

1) Objective 1: Minimization of Fuel Costs

a) Generator Fuel Cost Function

The generator fuel cost curves are modeled as a simple quadratic function expressed as

$$F_C(P_{GTkj}) = \sum_{k=1}^{N}\sum_{j=1}^{N_{GTk}} a_{kj} + b_{kj}P_{GTkj} + c_{kj}P_{GTkj}^2 \tag{1}$$

where N is the number of areas, N_{GTk} is the number of generators committed to the operating system in area k, a_{kj}, b_{kj}, c_{kj} are the fuel cost coefficients of the jth generator in area k, and P_{GTkj} is the real power output of the jth thermal generator in area k.

b) Tie Line Transmission Cost Function

The cost of transmitting power from one area to another and the tie line losses are lumped together and expressed as in [22] as

$$F_t(P_T) = \sum_{k=1}^{N-1}\sum_{l=k+1}^{N} f_{kl}P_{Tkl} \tag{2}$$

where P_{Tkl} is the active power transferred from area k to area l, f_{kl} is the transmission cost coefficient relevant to P_{Tkl} and P_T is the vector of real power transmission given by

$$P_T = [P_{T1,2},\ldots,P_{T1,k},P_{T2,3}\ \ldots,P_{T2,k},\ldots P_{Tk-1,k}$$

The power exchange between any two interconnected areas k and l are expressed as in [20] as equal but opposite

$$P_{Tkl} = -P_{Tlk} \tag{3}$$

The Total Generator Cost function is then calculated as in [22] and expressed as

$$F_{FC}(P_{GTkj}) = F_C(P_{GTkj}) + F_t(P_{Tkj}) \tag{4}$$

where $F_{FC}(P_{GTkj})$ is the total generation fuel cost function considering exports and imports, $F_C(P_{GTkj})$ is the fuel cost function of thermal generators and $F_t(P_{Tkj})$ is the transmission cost function of imports/exports.

2) Objective 2: Minimization of Emissions

The main gaseous pollutant emission of fossil fuelled thermal plants which is NO_X, is modelled as in [24] as a quadratic functions expressed as

$$F_E(P_{GTkj}) = \sum_{k=1}^{N}\sum_{j=1}^{N_{GTk}} \alpha_{kj} + \beta_{kj}P_{GTkj} + \gamma_{kj}P_{GTkj}^2 \tag{5}$$

where α_{kj}, β_{kj} and γ_{kj} are the emission coefficients of the j^{th} thermal generator in area k.

The complex multi objective problem is then formulated as in [25] as a minimization problem given by,

$$Min\ F = [F_{FC}(P_{GTkj}), F_E(P_{GTkj})] \tag{6}$$

where $F_{FC}(P_{GTkj})$ is the total generation fuel cost function of thermal generators and $F_E(P_{GTkj})$ is the NO_X emission function.

The two conflicting objectives are combined into one objective in (7) using weighted function method as in [11],

$$Min\ F = \left[\mu F_{FC}(P_{GTkj}) + (1-\mu)F_E(P_{GTkj})\right] \tag{7}$$

where μ is the weighting factor.

3) Power Output of Hydro Plant

The power output of a Hydro generating plant is expressed as

$$P_{GHkr} = C_{1kr}V_{Hkr}^{2} + C_{2kr}Q_{Hkr}^{2} + C_{3kr}V_{Hkr}Q_{Hkr} + C_{4kr}V_{Hkr} + C_{5kr}Q_{Hkr} + C_{6kr} \tag{8}$$

where $C_{1kr}, C_{2kr}, C_{3kr}, C_{4kr}, C_{5kr}$ and C_{6kr} are the coefficients of r^{th} hydro turbine in area K, V_{Hkr} is the storage volume of the r^{th} reservoir at time t and Q_{Hkr} is the water flow rate of the r^{th} reservoir at time t.

B. Constraints

The objective function in (7) is solved subject to the following constraints:-

1) Generator Capacity Constraint

The power output of each generator is restricted within its minimum and maximum limits for stable operation. These limits are expressed as in [26] as

$$P_{GTkj}^{min} \le P_{GTkj} \le P_{GTkj}^{max} \tag{9a}$$

$$P_{GHkr}^{min} \le P_{GHkr} \le P_{GHkr}^{max} \tag{9b}$$

where P_{GTkj}^{min} and P_{GTkj}^{max} are the minimum and maximum power produced by the j^{th} thermal generator in area k and P_{GHkr}^{min} and P_{GHkr}^{max} are the minimum and maximum power produced by the r^{th} hydro generator in area k

2) Active Area power balance Constraint

The total power generation in area k must satisfy the total demand in area k (P_{Dk}) while considering exports and imports and transmission losses in area k as in [27]. This is expressed as

$$\sum_{j=1}^{N_{GTk}} P_{GTkj} + \sum_{r=1}^{N_{GHk}} P_{GHkr} = P_{Dk} + P_{Lk} + \sum_{l,l\neq k}^{k} P_{Tkl} \tag{10}$$

where P_{GTkj} is the power generated thermal plants in area k, P_{GHkr} is the power generated by hydro plants in area k as given by (8), P_{Dk} is the total demand in area k, P_{Tkl} is the power transferred from or to area k and P_{Lk} is the total transmission loss in area k which is defined by Kron's Formula in [28] and expressed as

$$\sum_{k}^{N} P_{Lk} = \sum_{k}^{N}\left(\sum_{i=1}^{N_{Gk}}\sum_{j=1}^{N_{Gk}} P_{Gkj}B_{kij}P_{Gki} + \sum_{j=1}^{N_{Gk}} B_{0kj}P_{Gkj} + B_{00k}\right) \tag{11}$$

where i and j are generators in area k, and B_{kij}, B_{0kj} and B_{00k} are the line loss coefficients.

3) Tie Line Capacity Limits

For security considerations, the transfer of real power from one area to another e.g. area k to l, should not exceed the tie line transfer capabilities. This is expressed as:

$$-P_{Tkl}^{max} \le P_{Tkl} \le P_{Tkl}^{max} \tag{12}$$

where P_{Tkl}^{max} is the maximum power transfer capacity limit of the tie line connecting areas k and l.

4) Hydro Generating Unit Constraints

a) Dynamic Water Balance Equation

This is formulated for every reservoir assuming no time delays as:

$$V_{Hkr} = V_{Hkr} + (I_{Hkr} - Q_{Hkr} - S_{Hkr})] \tag{13}$$

where V_{Hkr} is the storage volume of r^{th} reservoir in area k, I_{Hkr} is the inflow rate into r^{th} reservoir in area k, Q_{Hkr} is the outflow rate from the r^{th} reservoir in area k, and S_{Hkr} is the spillage rate of the r^{th} reservoir in area k.

b) Discharge rates limits

The rate of discharge of the reservoir should be within set minimum and maximum flow rates expressed as

$$Q_{Hkr}^{min} \le Q_{Hkr}(t) \le Q_{Hkr}^{max} \tag{14}$$

where Q_{Hkr}^{min} and Q_{Hkr}^{max} are the minimum and maximum outflow rates of r^{th} reservoir in area k.

c) Reservoir Storage limits

The amount of water in the reservoir should be between the minimum and maximum capacities of the reservoir. This is expressed as:

$$V_{Hkr}^{min} \le V_{Hkr} \le V_{Hkr}^{max} \tag{15}$$

where V_{Hkr}^{min} and V_{Hkr}^{max} are the minimum and maximum volume of water of r^{th} reservoir in area k, V_{Hkr} is the actual volume of water of r^{th} reservoir in area k.

IV. Proposed Methodology

The methodologies which have been used in solving MAED optimization problem in the existing literature can generally be categorized into two groups: traditional mathematical programming methods and Meta heuristic optimization methods. The traditional mathematical programming methods include among others, Linear Programming Method [29], Analytical Techniques [15], and Direct Newton–Raphson Method [30]. These methods are less accurate due to linearization, easily get trapped in local optima positions and have high execution time.

To handle the shortcomings, Meta heuristic methods such as: Particle Swarm Optimization (PSO)[13][22], [26], [31], Backtracking Search Algorithm (BSA) [6], Flower Pollination Algorithm [7], Differential Evolution (DE) [11] etc. have been used to solve the complex multi objective MAED problem.

In this paper a new Meta heuristic algorithm known as Bat Algorithm (BA) which is inspired by the echolocation behaviour of micro bats is proposed to solve MOMAHEED problem. BA combines all the major advantages of PSO, GA and Harmony Search and has parameters which can be finely tuned for even faster convergence. The efficiency and accuracy of BA has been proven to be superior to other algorithms [32].

BA has been used in [7], [33], [24], [34]–[37] to solve ED problems.

A. *Bat Algorithm*

Bats are flying mammals that have advanced echolocation capability. Micro bats use echolocation to detect prey, locate their roosting crevices and avoid obstacles in the dark.
Bat algorithm is a meta heuristic algorithm developed by Xin She Yang in 2010 [32] which is inspired by the echolocation behaviour of micro bats.
Bat Algorithm can be formulated when some echolocation characteristics are idealized.
For simplicity, the following rules are considered:

i) All bats have a way to differentiate food, prey and other background barriers when they sense the distance to these objects by using echolocation.
ii) To search for food, Bats fly randomly with velocity V_i at position x_i with a fixed frequency f_{min} , varying wavelength λ and loudness A_o. Depending on how close their targets are, Bats either increase or decrease the wavelength (or frequency) of their emitted pulses and the rate of pulse emission r automatically.
iii) The loudness is assumed to vary from a large value A_o to a minimum constant value A_{min}.

In BA, the frequency $\boldsymbol{f_i}$ and velocities $\boldsymbol{v_i}$ are updated using (16) and (17) and thereafter positions $\boldsymbol{x_i}$ updated using (18) to obtain new solutions at time step t in the search space. That is:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \quad (16)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x_{best})f_i \quad (17)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (18)$$

where β is a random number between [0, 1] and x_{best} is the current global best location (or solution).

Local search is done by random walk where upon selection of the current best solutions, new solutions are generated locally by

$$x_{new} = x_{old} + \varepsilon A^t \quad (19)$$

where ε is a random number between [0, 1], and A^t is the average loudness of all the bats in this time step.
Bats increase pulse emission rates while decreasing the loudness as they approach the target. This is implemented by

$$A_i^{t+1} = \alpha A_i^t \quad (20)$$

$$r_i^{t+1} = r_i^0[1 - exp(-\gamma t)] \quad (21)$$

Bat Algorithm Pseudo Code

Objective function f(x), $x = (x_1, ..., x_d)^T$
Initialize the bat population i.e Position x_i *and velocities* V_i for i = 1, 2, ..., n
Define pulse frequency f_i *at* x_i
Initialize pulse rates r_i *and the loudness* A_i
while *(t <Max number of iterations)*
Generate new solutions by adjusting frequency,
and updating velocities and locations/solutions [equations (16) to (18)]
if *(rand >* r_i*)*
Select a solution among the best solutions
Generate a local solution around the selected best solution
end if
Generate new solutions by flying randomly (equation 19)
if *(rand <* A_i & $f(x_i) < f(x_{best})$*)*
Accept the new solutions
Increase r_i *and reduce* A_i *(20 & 21)*
end if
Rank the bats and find the current best x_{best}
end while
Post-process results and visualization

The parameters of Bat Algorithm are as shown in Table I

TABLE I. PARAMETERS OF BAT

Parameter	Value
Population of Bats	30
Fitness	$Min\ F$
Velocity v_i	From 0
Position X_i	$P_{GHkj}^{min} \le P_{GHkj} \le P_{GHkj}^{max}$ $Q_{Hkr}^{min} \le Q_{Hkr} \le Q_{Hkr}^{max}$
Frequency f_i	From 0
Pulse rate A_i	Rand [0,1]
Loudness r_i	Rand [1,2]

B. *Cardinal Priority Ranking*

Equation (7) generates non inferior solutions with explicit trade-offs between the conflicting objectives. Membership functions are defined which relate to the objectives by exploiting the Fuzzy decision making theory, to find the optimal trade-off level among the non inferior solutions. The membership function $\mu(F_i)$ given by:

$$\mu(F_i) = \begin{cases} 1 & F_i \le F_{imin} \\ \dfrac{F_{imax} - F_i}{F_{imax} - F_{imin}} & F_{imin} \le F_i \le F_{imax} \\ 0 & F_{imax} \le F_i \end{cases} \quad (22)$$

where F_{imax} and F_{imin} are the minimum and maximum values of i^{th} objective function where the solution is expected.
The 'accomplishment' which indicate how much a non-dominated solution has satisfied the i^{th} is then normalized over the sum of the 'accomplishments' of all the non-dominated solutions as:

$$\mu_D^k = \frac{\sum_{i=1}^{L} \mu_k(F_i)}{\sum_{k=1}^{N} \sum_{i=1}^{L} \mu_k(F_i)} \quad (23)$$

The accomplishments μ_D^k result in a set of non dominated solutions, from which the maximum value is selected as the optimal result.

V. RESULTS DISCUSSIONS AND ANALYSIS

This section discusses the results of the simulations used to evaluate the performance of Bat Algorithm. The algorithm was implemented in Matlab R2015a on an Intel Core i7, 2.5GHz PC with 8GB memory. Various cases are considered for a four area, three Thermal Units test system whose data is taken from [23].

a) Test Case 1

In this case, BA is tested for MAED Problem (Minimizing Fuel cost only) and results in total fuel cost of 2049.49$/hr with total emissions of 2168.77Kg/hr as shown in Table II.

TABLE II. MAED

	Area 1	Area 2	Area 3	Area 4
P1(MW)	35.00	150.00	175.00	175.00
P2(MW)	153.39	110.00	200.54	215.00
P3(MW)	325.00	155.29	215.00	228.00
Ploss (MW)	13.40	5.83	12.70	18.00
Ptotal	513.39	415.29	590.54	618.00
Emissions (Kg/hr)	465.99	282.47	932.25	488.06
Total Emissions (Kg/hr)	2168.77			
Fuel Cost($/hr)	389.66	386.67	644.73	628.43
Total Fuel Cost ($/hr)	2049.49			

b) Test Case 2

In this case, BA is tested for MAEED problem (simultaneously curtailing fuel cost and emissions) and results in total fuel cost of 2226.17$/hr with total emissions of 2034.74Kg/hr as shown in Table III. The fuel cost increases slightly by 8.6% as a result of the addition of emission cost to the fuel cost minimization function but this reduces emissions by 6.2%.

TABLE III. MAEED

	Area 1	Area 2	Area 3	Area 4
P1(MW)	38.44	141.51	162.38	174.28
P2(MW)	275.59	96.17	91.94	113.45
P3(MW)	199.73	177.51	335.00	327.70
P_{loss} (MW)	13.08	5.66	12.36	18.86
P_{total}	513.77	415.20	588.53	615.44
Emissions (Kg/hr)	406.04	294.15	890.93	443.62
Total Emissions (Kg/hr)	2034.74			
Fuel Cost($/hr)	396.71	394.61	761.59	673.28
Total Fuel Cost ($/hr)	2226.19			

c) Test Case 3

In this case, the BA is tested on a four area system each with three thermal generators with an additional hydroelectric units of 100MW in areas 3 and 4. MOMAHEED problem is solved in this case and results in total fuel cost of 1937.88$/hr with total emissions of 1488.65Kg/hr as shown in table IV.

By introducing hydroelectric generating units into MAEED problem, the total fuel cost is reduced by 13% and total emissions reduced by 26.8%, since some of the electricity generated by thermal plants is displaced by the hydroelectric generation which has zero fuel cost and zero emissions.

Results of MAED, MAEED and MOMAHEED are compared in table V.

TABLE IV. MOMAHEED

	Area 1	Area 2	Area 3	Area 4
P1(MW)	96.95	130.93	151.81	168.09
P2(MW)	181.42	100.16	110.89	52.97
P3(MW)	227.97	184.09	228.98	291.77
P_{Hydro}(MW)	0	0	100.00	100.00
P_{loss} (MW)	11.90	5.61	8.76	13.42
P_{total}	506.34	415.18	591.68	612.82
Emissions (Kg/hr)	319.24	298.95	524.04	346.42
Total Emissions (Kg/hr)	1488.65			
Fuel Cost($/hr)	461.17	393.30	564.87	517.54
Total Fuel Cost ($/hr)	1937.88			

TABLE V. COMPARISON OF MAED, MAEED AND MOMAHEED

	MAED	MAEED	MOMAHEED
Total Fuel Cost ($/hr)	2049.49	2226.19	1937.88
Total Emissions (Kg/hr)	2168.77	2034.74	1488.65

d) Results Comparison and Analysis

BA results in fuel costs reduction of 45% and increase in emissions of 24% when compared to PSO [23] for the same MAEED problem as presented in table VI. While BA results in total fuel cost of 2226.17$/hr with total emissions of 2034.74Kg/hr, PSO results in total fuel cost of 4046.21$/hr with total emissions of 1645.2Kg/hr.

TABLE VI. COMPARISON OF BA AND PSO IN MAEED

	PSO [23]	BA	% Difference
Fuel Cost($/hr)	4046.21	2226.17	45% Reduction
Emissions (Kg/hr)	1645.2	2034.74	24% Increase

VI. CONCLUSION

In this paper MAED problem has been formulated and solved for the first time for a hydrothermal system while considering emissions using Bat Algorithm. This formulation accurately represent most practical power pools which are hydrothermal systems. The use of Bat Algorithm has resulted in 45% lower fuel costs when compared to PSO for the same system.

In future work Bat Algorithm can be hybridized with other algorithms to make it more robust and used to solve MOMAHEED problem.

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