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Water Wave Optimization Algorithm for Solving Economic Dispatch Problems with Generator Constraints

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Abstract: This paper presents the application of Water Wave Optimization Algorithm (WWOA) for solving economic dispatch problems including practical generator constraints. WWOA is inspired by the shallow water wave theory. The efficiency of the WWO Algorithm for solving economic dispatch problems is demonstrated by implementing it on three test systems having three, six and fifteen generating units with non-linear characteristics of the generator such as ramp-rate limits, prohibited operating zones including the system transmission losses. The results of the proposed approach have been compared with existing results obtained by other solution techniques. The test results reveal the capability of the proposed algorithm as an effective tool for solving various economic dispatch problems in a power system.

Keywords: Water Wave Optimization Algorithm (WWOA); Economic load dispatch; ramp-rate constraints; prohibited operating zones; transmission losses; cost minimization.

1. Introduction

The economic load dispatch (ELD) is an essential and fundamental element in the optimal operation and control of modern power systems. Though the foremost objective of the economic dispatch problem is to reduce the total operating cost with the best combination of power outputs satisfying the total load demand and losses, many constraints like valve-point loadings, ramp-rate limit, prohibited operating zones etc., make the optimization problem highly nonlinear especially for larger power systems [1].

Some physical limitations, such as faults in machines or in its associated auxiliaries (boiler, feed pumps), make the units to have certain regions prohibited for operation termed as prohibited operating zones (POZs). The generators are not allowed to operate in these regions as they may experience increased vibrations in their shaft bearings that have to be prevented in real-time operation. Also due to unit generation output change restrictions, the real-time operating units can have ramp-rate limits [2].

The emphasis on direct search and stochastic methods is due to the observation that mathematical programming approaches are often not suitable for tackling such problems due to the non-convexity of the search space.

In traditional methods like lambda-iteration, gradient, base point method etc., the cost function is modelled as a single quadratic function but in practice the operating conditions of various generators are different and the input-output characteristics is remodelled as a piecewise quadratic function in the thermal power plants [3]. Even though the dynamic programming has no restrictions on the characteristics of the cost curves, they cause the dimension of the problem to be high which in turn requires more computational efforts to solve the problem [4]. For the past several years several AI techniques such as genetic algorithm, evolutionary programming [5, 6], differential evolution [7, 8, 9], particle swarm optimization [10, 11, 12, 20], biogeography based optimization [13, 14], artificial bee colony algorithm [15, 16], exchange market algorithm [18] are employed to find the optimal solution for the economic dispatch problems.

Although there are several methods available for the economic dispatch problem, the larger the system, greater is the complexity which necessitates developing efficient algorithms to stably find an optimal solution. In this context, the focus of this work is to demonstrate the efficiency of a nature inspired approach for solving ELD problems of varying complexity.

In the first, the water wave theory was related to gravitational force and other forces dating back to Newton's work in 1687 [20] and later by the development of mathematical models like Laplace. Lagrange, Poisson made the linear wave theory advanced along with non-linear waves as considered by Stokes, Gerstner and Kelland [21].

Recently, a new metaheuristic optimization technique called Water Wave Optimization Algorithm (WWOA) has been proposed by Zheng [17] which is inspired by the shallow water wave models. Here, the idea is from the wave motions, which is controlled by the wave-current-bottom interactions and the wave turbulence theory [21, 22] in the search mechanism design for high dimensional optimization problems. The WWOA maintains the population of solutions, each of which is analogous to a "Wave" with a height 'h' and a wavelength 'λ'. In this paper, the WWOA is used for obtaining the solutions for ELD problems with generator constraints. The major advantage of the proposed method is it's easy to implement, requires lesser number of population vectors, fewer control parameters and hence are very effective in search for the best solution in a high dimensional search space. To show the competitive nature and efficiency of WWOA, it is compared with some of the familiar metaheuristics techniques that were proposed in the recent years [7, 11, 18, 19].

The remaining of the paper is organized as follows: Section 2 describes different cases of economic dispatch problems. The three phases of WWO Algorithm and their mathematical model is presented in Section 3. Section 4 deals with the implementation part of the WWO Algorithm to economic dispatch problems. The results of the WWOA implementation to numerical test systems with 3, 6, 15 units are compared with a few popular techniques with illustration and are presented in Section 5.

In order to emphasize the capability of the WWO Algorithm, the technique is applied to various convex and non-convex economic dispatch problems considering the existence of power system losses, ramp-rate limits and the prohibited operating zones.

2. Problem formulation

2.1 Objective function

The main objective of the ELD problem is to determine the optimal combination of power generations that minimizes the total generation cost satisfying the generator constraints. The traditional objective function of the ELD problem can be approximately represented as a single quadratic function.

Minimizing the overall operational cost

The overall operational cost is the sum of production cost and variable operation and maintenance cost. The objective function of minimizing the overall operational cost over the plan ning period is stated as,

$$Min\ \ F_T = \sum_{i=1}^{N_g} F_i(P_{Gi}), \qquad (\$/h) \qquad (1)$$

Hence, the fitness function to be maximized is

$$Max \quad F_T = -\left[\sum_{i=1}^{Ng} F_i\left(P_{Gi}\right) + h_{pp}\left[\left(P_D + P_L\right) - \sum_{i=1}^{Ng} P_{Gi}\right]^2\right] (\$/h) \qquad (2)$$

where $F_i\ (P_{Gi}) = a_i + b_i P_{Gi} + c_i P_{Gi}^2,\ (\$/h)$, i = 1, 2,…,$N_g$. F_T is the total generation cost ($/h); F_i is the cost function of the i^th^ generator; a_i, b_i, c_i are the cost coefficients of the i^th^ generator, P_{Gi} is the power output (MW) of the i^th^ generator and N_g is the number of generators, h_{pp} is the penalty factor, P_D is the total power demand (MW). P_L is the total power loss (MW).

2.2 Power balance constraints

The total power generated should be equal to the total load demand (P_D) along with the transmission line loss (P_L) as given by,

$$\sum_{i=1}^{N_g} P_i = P_D + P_L \qquad (3)$$

The loss can be calculated using B-loss coefficients by Kron's formula as,

$$P_L = \sum_{i=1}^{N_g}\sum_{j=1}^{N_g} P_i . B_{ij} . P_j + \sum_{i=1}^{N_g} B_{0i} . P_i + B_{00} \qquad (4)$$

where $B_{ij},\ B_{0i},\ B_{00}$ are the B coefficients.

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2.3 Generator capacity constraints

The generated power output (P_i) of each generator should vary within its minimum ($P_{i,min}$) and maximum ($P_{i,max}$) limits. This inequality constraint is represented as,

$$P_{i,min} \leq P_i \leq P_{i,max} \quad (5)$$

2.4 Ramp-rate limits

The power generated by the i^th generator p_i^o in certain interval (t) may neither exceed the previous interval (t-1) generation p_i^o by more than UR_i (up-ramp rate limit) nor less than DR_i (down-ramp rate limit). This constraint is represented as,

$$\max(p_i^{min}, p_i^0 - DR_i) \leq p_i \leq \min(p_i^{max}, p_i^0 + UR_i) \quad (6)$$

i.e., as generation increases or decreases, p_i - $p_i^o \leqslant URi$ (or) p_i^o-$pi \leqslant DRi$ should be maintained respectively.

2.5 Prohibited operating zones

In practice, the machine operations are limited by boiler, feed pumps etc. The prohibited operating zones are the range of power output of a generator where the operation causes vibrations of the turbine shaft bearing caused by the opening and closing operations of the steam valve. The machines or their accessories may get damaged if they are made operate in these prohibited operating regions. To avoid these kinds of faults the generated power output should satisfy the POZ constraint. The permitted operating zones of generation is defined as,

$$\begin{cases} P_{i,\,min} \leq P_i \leq P_{i,\,1}^l \\ P_{i,\,k-1}^u \leq P_i \leq P_{i,\,k}^l \\ P_{i,\,z}^u \leq P_i \leq P_{i.\,max} \end{cases} \quad (7)$$

where $p_{i,k}^l$and $p_{i,k}^u$are the lower and upper limits of k^{th} prohibited zone respectively. z is the number of prohibited operating zones for the i^th generator.

3. Water wave optimization algorithm

3.1 Inspiration

Nature has been the main source of inspiration for the majority of the population-based stochastic optimization techniques which performs the optimiz ation randomly. The optimization process is usually started by creating a set of random solutions. These initial solutions are then combined, moved, or evolved over a predefined number of steps called iterations or generations. This is almost the main framework of all population-based algorithms. In this paper, the application of Water Wave Optimiz ation Algorithm (WWOA) is proposed to solve the economic dispatch problems with certain constraints. The WWO Algorithm was introduced by Zheng in the year 2015[17].

The WWOA has three important phases for finding solution to the problem at hand. They are wave propagation, breaking and refraction phase. In Wave propagation, the wave is propagated to a random position exactly once in an iteration. If a wave attains a lower sea depth (best fitness), it breaks into solitary waves which are formed in the breaking phase. Thus breaking is used for the intensive search (exploitation) in search spaces by producing random solitary waves around the current best position. While in the Refraction phase, the algorithm explores the search space for any other best solution and avoids search inactiveness (stagnation). Overall, these three phases plays a vital role in the finding optimal or near optimal solution for the problem. Here, each solution is represented as a ‘wave’ with corresponding height (h) and wavelength (λ).

3.2 Mathematical model of WWO Algorithm

In prelude to the proposed WWO Algorithm (WWOA), the mathematical model of propagation, breaking and refraction is provided first.

3.2.1 Propagation

From the wave population, each wave is allowed to propagate only once in each iteration. Here the propagation operator shifts the original wave x in each dimension to produce a new propagated wave x'. The new wave is modelled by the following equation:

$$x'(d) = x(d) + rnd(-1,1).\lambda.L(d) \quad (8)$$

where $rnd(-1,1)$ is a uniformly distributed random number within the range [-1, 1] and $L(d)$ is the length of the d^th dimension. λ is the wavelength of wave x, which is updated after each generation, as follows:

$$\lambda = \lambda.\alpha^{-(f(x)-f_{min}+\epsilon)/(f_{max}-f_{min+\epsilon})} \quad (9)$$

where α is the wavelength reduction coefficient, where f(x) is the fitness of the original wave, f_{max} and f_{min} are respectively the maximum and minimum fitness values among the current population and ϵ is a very small positive number to avoid division-by-zero. The Eq. (9) ensures that the waves with higher fitness value have lower wavelengths and thus propagate with smaller ranges.

3.2.2 Breaking

In WWOA, the breaking operation is performed only on a wave x that finds a new best solution (i.e., x becomes the new x^*) and conduct a local search around x^* using 'k' solitary waves to simulate wave breaking using Eq. (10).

$$x'(d) = x(d) + N(0,1).\beta.L(d) \quad (10)$$

where β is the breaking coefficient. N is the Gaussian random number, *L(d)* is the length of the d^{th} dimension. If none of the solitary waves are better than x^*, x^* is retained; otherwise x^* is replaced by the fittest one among the solitary waves. Totally k number of solitary waves x' are generated at each dimension d and the value of k is generated randomly between 1 and k_{max}.

3.2.3 Refraction

During wave propagation, if the wave path is not perpendicular to the isobaths the wave gets deflected and the wave converges in shallow regions and diverges in deep regions. In WWOA, refraction is performed on the waves whose height decreases to zero. The position of the wave after refraction is calculated as,

$$x'(d) = N\left(\frac{x^*(d)+x(d)}{2}, \frac{|x^*(d)-x(d)|}{2}\right) \quad (11)$$

where N is a Gaussian random number, x^* is the best solution found so far and d is the dimension of the problem. So the new position of the wave is a random number midway between the original and the current best known position. Once the refraction phase is ended, the wave height of x' is reset to its maximum value h_{max} and its wavelength is set by,

$$\lambda' = \lambda \frac{f(x)}{f(x')} \quad (12)$$

4. Implementation of WWO Algorithm for ELD problem

There are four main control parameters in WWO Algorithm apart from the population size. They are: the maximum wave height h_{max}, the wavelength reduction coefficient α, the breaking coefficient β, and the maximum number k_{max} of breaking directions. In all our test system the parameters, α = 1.01, β = 0.001, and h_{max}= 6 are used for the study of economic dispatch problems and the maximum number of iterations is considered as the stopping criteria. The following are the parameter selection range as recommended by Zheng [17] in his literature.

4.1 Parameter selection range

Wavelength reduction coeff.(α) = (1.001 to 1.01)
Breaking coefficient (β) = (0.001 to 0.01)
Maximum wave height(h_{max}) = 5 or 6
Initial Wavelength (λ) = 0.5
Max. No. of breaking direction k_{max}= min(12, D/2)
where, D is the problem dimension.

The flow chart of the proposed WWO Algorithm implemented to solve the economic dispatch problem is shown in figure 1.

5. Numerical simulation results and discussion

The WWO Algorithm was applied on three different test systems for investigating the optimization capability: The three test systems considered are (1) 3-unit system (2) 6-unit system and (3) 15-unit system. All three test systems are with ramp rate limits, prohibited operating zones and network losses. In order to verify the feasibility and efficiency performance of the proposed algorithm, it has been compared to other population based optimization techniques like, IDP [7], PSO [11], EMA [18] and GA [19]. When compared to the existing techniques, the proposed technique obtains quality solution with lesser number of iterations, minimum number of population vectors and fewer control parameters.

5.1 Test system 1: 3 units system

The system consists of three thermal units whose characteristics are given in table 1 and the data are taken from [18] that include transmission loss, ramp-rate limits and prohibited operating zones. The system load is set at 300 MW.

The kron's loss formula B-coefficients are taken from [19]. Here it is aimed to optimize or reduce the total fuel cost of the system including transmission losses and make it operate adapting the ramp-rate limits and prohibited operating zones.

The results obtained by the proposed algorithm on test system with three units and its comparison with EMA and GA are presented in table 2.

The convergence profile comparison of the cost function is depicted in figure 2. The comparison of generator power outputs by WWOA and other algorithms is shown in figure 3.

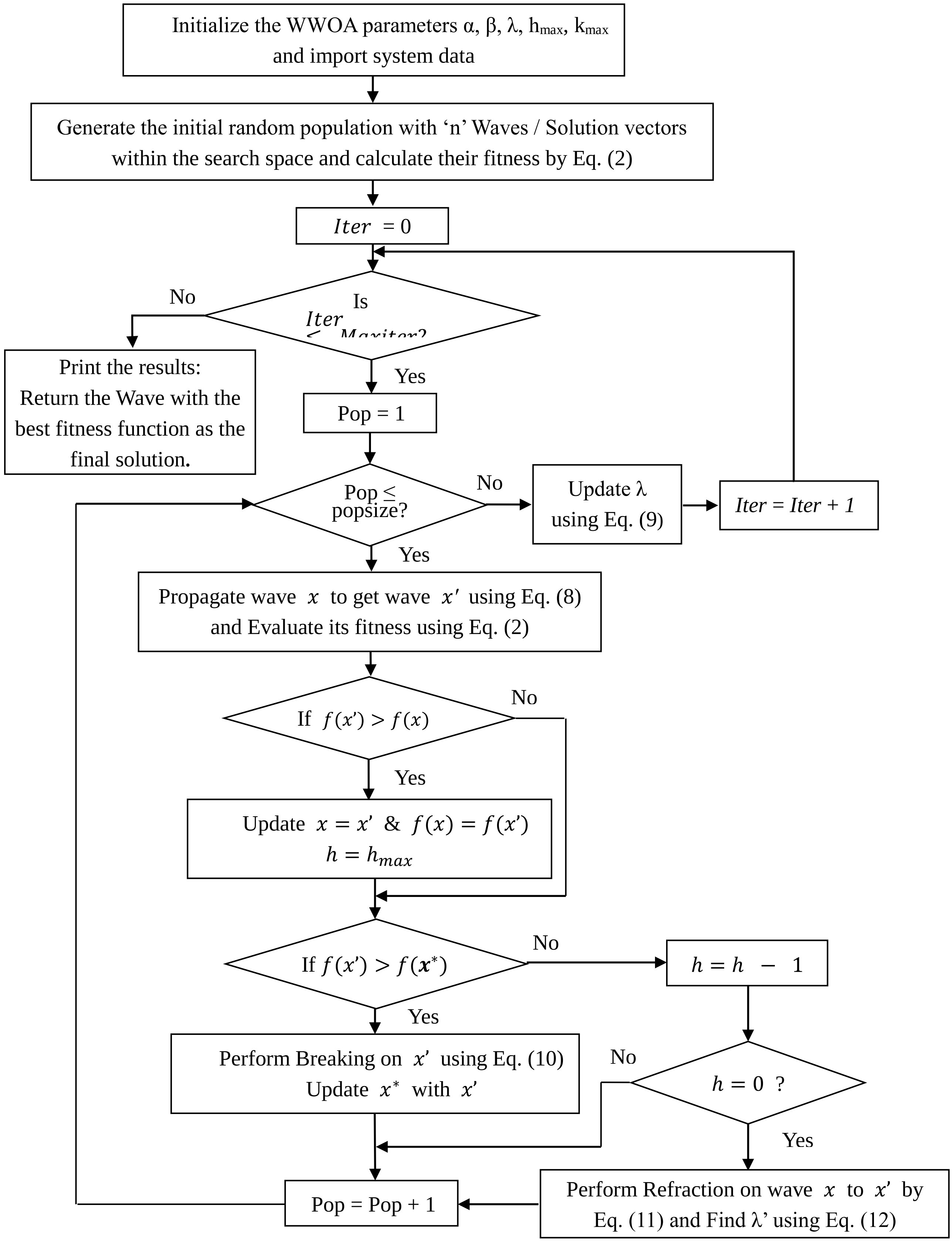

Figure.1 Flow chart of WWOA implementation for ELD problem

Table 1. Operating characteristics data for 3, 6 and 15 unit systems

Unit	$P_{i,min}$ (MW)	$P_{i,max}$ (MW)	a_i ($/h)	b_i ($/MWh)	c_i ($/MW²/h)	UR_i (MW)	DR_i (MW)	P_i^0 (MW)	Prohibited Operating Zones (MW)
3 units system									
1	50	250	328.13	8.663	0.00525	55	95	215	[105,117] [165,177]
2	5	150	136.91	10.04	0.00609	55	78	72	[50,60] [92 102]
3	15	100	59.16	9.76	0.00592	45	64	98	[25,32] [60,67]
6 units system									
1	100	500	240	7	0.0070	80	120	440	[210, 240] [350, 380]
2	50	200	200	10	0.0095	50	90	170	[90, 110] [140, 160]
3	80	300	220	8.5	0.0090	65	100	200	[150, 170] [210, 240]
4	50	150	200	11	0.0090	50	90	150	[80, 90] [110, 120]
5	50	200	220	10.5	0.0080	50	90	190	[90, 110] [140, 150]
6	50	120	190	12	0.0075	50	90	110	[75, 85] [100, 108]
15 units system									
1	150	455	671	10.1	0.000299	80	120	400	-
2	150	455	574	10.2	0.000183	80	120	300	[185, 225] [305, 335] [420, 450]
3	20	130	374	8.8	0.001126	130	130	105	-
4	20	130	374	8.8	0.001126	130	130	100	-
5	150	470	461	10.4	0.000205	80	120	90	[180, 200] [305, 335] [390, 420]
6	135	460	630	10.1	0.000301	80	120	400	[230, 255] [365, 395] [430, 455]
7	135	465	548	9.5	0.000364	80	120	350	-
8	60	300	227	11.2	0.000338	65	100	95	-
9	25	162	173	11.2	0.000807	60	100	105	-
10	25	160	175	10.7	0.001203	60	100	110	-
11	20	80	186	10.2	0.003586	80	80	60	-
12	20	80	230	9.9	0.005513	80	80	40	[30, 40] [55, 65]
13	25	85	225	13.1	0.000371	80	80	30	-
14	15	55	309	12.1	0.001929	55	55	20	-
15	15	55	323	12.4	0.004447	55	55	20	-

Table 2. Comparison of results for a three unit system (Pd=300 MW)

Unit (MW)	WWOA (Proposed)	EMA [18]	GA [18]
P1	200.2231	200.5892	194.265
P2	78.6042	78.2520	50.000
P3	34.0000	34.0000	79.627
$\sum P_{Gi}$	312.8274	312.8413	323.89
P_{Loss}	12.8274	12.8413	24.011
T. Gen. Cost ($/h)	3634.7374	3634.7683	3737.20

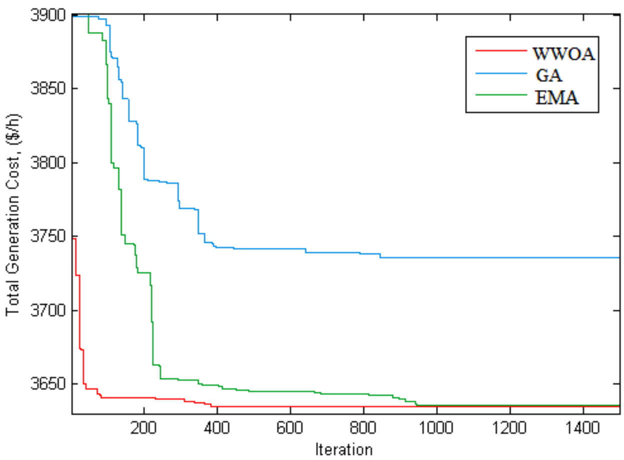

Figure.2 Convergence characteristics comparison of WWOA with other methods for a three unit system

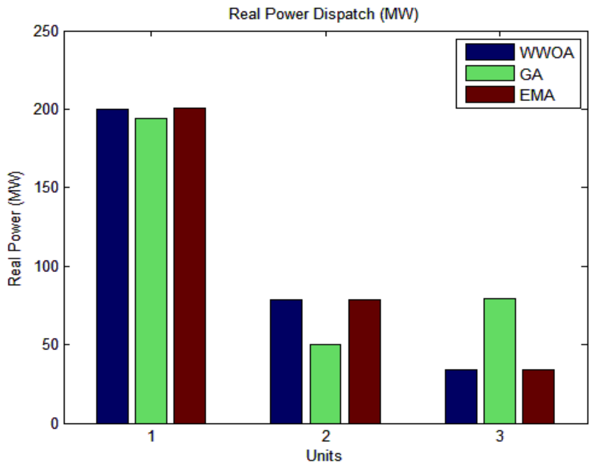

Figure.3 Generator outputs by WWOA compared with other algorithms for a three unit system

5.2 Test system 2: 6 units system

The test system has six thermal units and transmission losses are considered. The cost coefficients, minimum and maximum generation limits, ramp-rate limits and prohibited operating zones [18] of the generating units are given in table 1. The system load demand is 1263 MW. Table 3 shows the revised operating regions after considering the prohibited operating zones and the ramp-rate constraints. The B-loss coefficients with base capacity of 100 MVA are used to calculate the transmission loss which is taken from [11]. The results obtained by solving the six unit test system are given in table 4 and its convergence characteristic is shown in figure 4. The comparison of generator power outputs by WWOA with the algorithms compared is shown in figure 5.

Table 3. Operating regions after considering the prohibited operating zones and ramp-rate constraints for a six unit system

Units (MW)	Operating region 1	Operating region 2	Operating region 3
1	(320-350)	(380-500)	-
2	(80-90)	(110-140)	(160-200)
3	(100-150)	(170-210)	(240-265)
4	(60-80)	(90-110)	(120-150)
5	(110-140)	(150-200)	-
6	(50-75)	85-100)	(105-120)

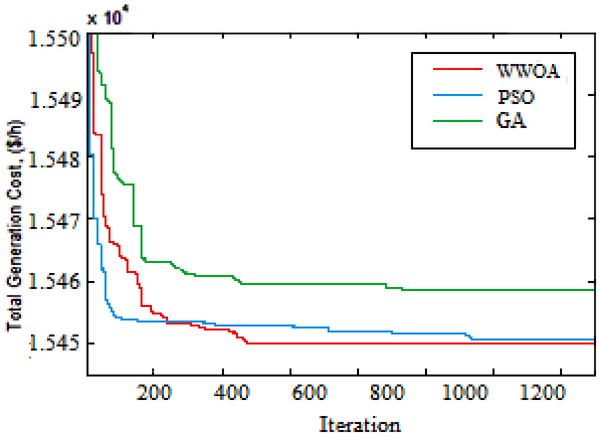

Figure.4 Convergence characteristics comparison of WWOA with other methods for a six unit system

The proposed algorithm without any roundup values of the computed output powers, produced the best solution as 15,449.8991 ($/h). Figure 4 shows the comparison of convergence characteristics of proposed algorithm with PSO and GA techniques. From above figure, it is clear that WWOA finds better optimal solution than other algorithms considered. Also, the convergence speed of the proposed algorithm to reach the optimal solution is better when compared to other methods. The result of IDP method [7] is also compared in table 4 and since it is a mathematical approach, the convergence characteristic is not shown in the above figure.

The loss coefficients used from the references cited in the comparison table are four decimal places rounded up from the original loss coefficients.

5.3 Test system 3: 15 units system

In this fifteen-thermal units test system, the basic constraints and non-linear characteristics of the economic dispatch problem are implemented. The ramp-rate limits, prohibited operating zones and network transmission losses are also considered for demonstrating the proposed method and the test system's input data is taken from [18]. To ensure global optimum solution, a 50 different runs were performed by varying the total number of objective function evaluations. From the results it is observed that performance of the proposed approach is found to be better in terms of solution quality and convergence speed than the compared methods.

The input data for this system is provided in table 1. The load demand of the system is 2630 MW. The B-loss coefficient values for calculating the losses are taken from [11].

Table 4. Comparison of results for six units system (Pd=1263 MW)

Unit	**WWOA (Proposed)**	**PSO [11]**	**IDP [7]**	**GA [11]**
P1	447.4982	447.4970	450.9555	474.8066
P2	173.3397	173.3221	173.0184	178.6363
P3	263.5061	263.4745	263.6370	262.2089
P4	139.0724	139.0594	138.0655	134.2826
P5	165.42	165.4761	164.9937	151.9039
P6	87.12139	87.1280	85.3094	74.1812
$\sum P_{Gi}$	1275.9576	1276.01	1275.98	1276.03
P_{Loss}	12.9576	12.9584	12.9794	13.0217
T. Gen. Cost ($/h)	15449.8991	15450	15450	15459

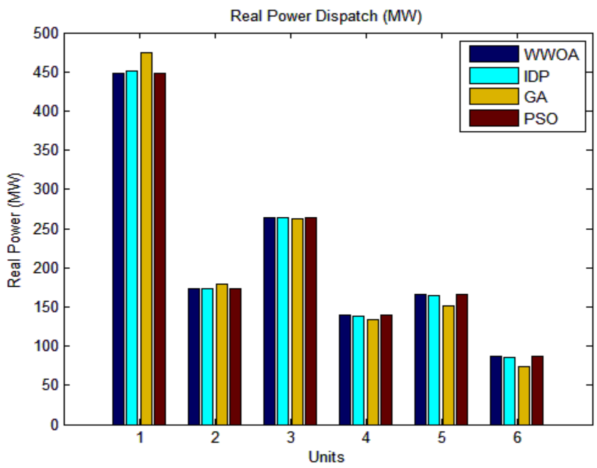

Figure.5 Generator outputs by WWOA compared with other algorithms for a six units system

Since the ramp-rate limits of the system restrict the operating range of the committed units between two operating periods, only the prohibited operating zone limits has to be considered. In this system, the units 2, 5, 6 and 12 have prohibited operating zones while the other nine units operate in their normal upper and lower limits. The regions of operation of these four units after including prohibited operating zone, ramp-rate limit constraints are given in table 5. The optimum generations of individual thermal units and the total fuel cost for a load demand of 2630 MW by the proposed algorithm and its comparison with other methodologies are reported in table 6.

The convergence plot comparison and the comparison of generator power outputs of WWO Algorithm for a fifteen unit test system are shown in figure 6 and figure 7 respectively.

Table 5. Operating regions after considering the prohibited operating zone and ramp-rate constraints for a fifteen unit system

Unit	**Operating region 1**	**Operating region 2**	**Operating region 3**
2	(240-305)	(335-420)	-
5	(150-180)	(200-270)	-
6	(280-365)	(395-430)	(455-460)
12	(20-30)	(40-55)	(65-80)

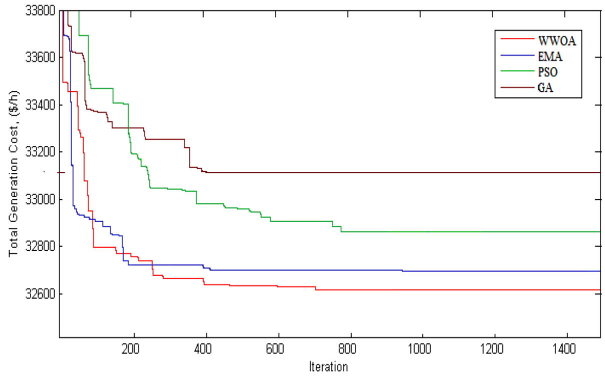

Figure.6 Convergence characteristics comparison of WWOA with other methods for a fifteen unit system

Table 6. Comparison of results for fifteen unit system

(Pd=2630 MW)

Unit	WWOA (Proposed)	EMA [18]	GA [11]	PSO [11]
P1	455	455	415.3108	439.1162
P2	440	380	359.7206	407.9727
P3	130	130	104.4250	119.6324
P4	13	130	74.9853	129.9925
P5	267.64	170	380.2844	151.0681
P6	460	460	426.7902	459.9978
P7	430	430	341.3164	425.5601
P8	60	72.0415	124.7867	98.5699
P9	25	58.6212	133.1445	113.4936
P10	46.0756	160	89.2567	101.1142
P11	79.6989	80	60.0572	33.9116
P12	79.6517	80	49.9998	79.9583
P13	25	25	38.7713	25.0042
P14	15	15	41.9425	41.4140
P15	15	15	22.6445	35.6140
$\sum P_{Gi}$	2658.0662	2660.6626	2668.4	2662.4
P_{Loss}	28.0662	30.6626	38.2782	32.4306
T. Gen. Cost ($/h)	32616.4668	32704.4503	33113	32858

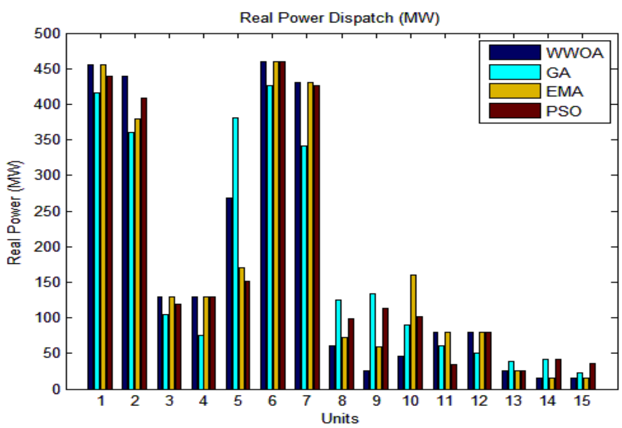

Figure.7 Generator outputs by WWOA compared with other algorithms for a fifteen unit system

6. Conclusion

In this paper, the economic dispatch problem of varying complexity has been considered and water wave optimization algorithm has been proposed to solve the problem. The problem has been subjected to various set of generator constraints. The analysis of the numerical simulation results renders the performance of the proposed algorithm for ELD problems. From the results it is observed that WWOA can be considered as a reliable tool to solve ELD problems which have the ability to converge to a better quality solution. WWOA can also be implemented for solving complex hydrothermal scheduling, optimal power flow and dynamic economic load dispatch problems in power systems.

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