Performance Evaluation of HEBMO for Non-convex Economic Dispatch Problems Under Contingencies

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***Abstract*— Economic dispatch study is important in the electric power industry because it is concerned with efficient electrical power production and economics. It is crucial to reduce the operating costs of electric energy because even small savings have a large impact on total generation costs and fuel consumption. This paper presents the proposed algorithm namely Hybrid Evolutionary-Barnacles Mating Optimization (HEBMO) to solve non-convex economic dispatch (ED) problems specifically under the line and generator outages. The evaluation is tested on two types of reliability test systems (RTS), named IEEE 30-Bus RTS and IEEE 57-Bus RTS. HEBMO is compared to a single optimization algorithm, EP and BMO for performance evaluation purposes. The results show that the HEBMO algorithm outperforms EP and BMO in terms of minimizing the generation cost. On the other hand, HEBMO also achieves a convincing performance in terms of fast computational time.**

Keywords*— *non-convex economic load dispatch, ramp rate limit, Evolutionary Programming, Barnacles Mating Optimizer

I. INTRODUCTION

The significant expansion in the consumption of fossil fuels over the last few decades has resulted in a global resource loss [1]. But, the rising demand for power from year to year also caused an increase in the price of fuel produced [2]. Therefore, optimal power generation is always an important topic among researchers. Economic dispatch (ED) is considered one of the critical issues in every power generating system because it is a procedure for allocating generation among available generating units to reduce total generation costs in satisfying the common restrictions in ED problems; the capacity of the generators, the valve point effect, the ramp-rate of generating units and the power balance.

As we know that electrical energy is prohibitively expensive to store in large amounts, and the demand from the users is constantly changing, the electric energy supplied by the power system must always maintain a dynamic balance with the demand of system loads to keep the entire system stable, to avoid the disruption of the system and affecting the system's safety [1].

Researchers are increasingly turning to metaheuristic optimization algorithms to solve complicated problems instead of using traditional optimization techniques. Metaheuristic optimization algorithms have the advantage of having a broad capability, in that they may be used to solve any problem that can be represented as a function optimization problem. Numerous single optimization techniques have been explored to solve convex and non-convex ED problems such as whale optimization algorithm [1], improved marine predators algorithm [3], multiverse optimization (MVO) [4], adaptive rooted tree [5], particle swarm optimization (PSO) [6], chaotic slime mould algorithm [7], teaching-learning algorithm [8][9], memetic sine cosine algorithm [10], dragonfly optimization [11],[12], krill herd optimization [13], gravitational search algorithm[14] and artificial cooperative search algorithm [15].

Subsequently, a hybrid method can combine two or more techniques to address the high complexities of practical ED problems [15]. Most studies found that the implementation of a hybrid strategy algorithm has proven as a better optimization tool than a single optimization algorithm, by providing a good quality result. Several of the research studies are; modified hybrid particle swarm optimization with bat algorithm [16], hybrid salp swarm and hill-climbing [17], hybrid Firefly-Accelerated PSO algorithm[18], GA-SQP algorithm [19], hill climbing with gravitational search algorithm [20], and Hybridizing of Whale and Moth-Flame Optimization Algorithms [21], Immune-Commensal-Evolutionary Programming [22], and MVO-SQP [23].

In this paper, a robust hybrid optimization based on Evolutionary Programming (EP) and Barnacles Mating Optimizer (BMO) is proposed to solve the non-convex ED problems, considering the valve point effect for accurate modeling of the generator cost. The advantage of the proposed algorithm is the capability in generating cost-efficient for generation costs when compared to the single optimization techniques, EP and BMO. A hybrid optimization algorithm has been implemented to overthrow the drawback of the single optimization algorithm, primarily premature convergence and trapped at the local optima. The effectiveness of HEBMO is validated using IEEE 30-Bus RTS and IEEE 57-Bus RTS under the line and generator outage contingencies.

II. PROBLEM FORMULATION

The objective function is a minimization of the total generation cost. The non-linear fuel cost function of thermal power generators is modeled as a quadratic function given as in (1).

$$F(P_G) = \sum_{i=1}^{N} a_i + b_i P_{Gi} + C_i P_{Gi}^2 \quad (1)$$

In the modeling of the non-convex characteristics of the problem due to the consideration of generator constraints, the valve point effect is written as the sum of a smooth quadratic part and a sinusoidal term making it concave and non-smooth.

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

In (1) and (2) a_i, b_i, c_i is the cost coefficients of the i^{th} generator, which are constants, e_i and f_i are the generator's coefficient for valve point effect, and P_i^{min} is the lower limit of the generator i.

Total power generation is always equal to total load demand, P_D and system losses, P_L in this constraint, and it will be written as

$$\sum_{i=1}^{N} P_{Gi} = P_D + P_L \quad (3)$$

The real power generated by each generating unit must be inside the lower bound, P_{Gi}^{min} and upper bound, P_{Gi}^{max} as in (4)

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (4)$$

where P_{Gi}^{max} and P_{Gi}^{min} are the maximum and minimum real power at generating unit, i^{th} respectively. The real power limitation must be considered for completing a stable operation.

III. IMPLEMENTATION OF HEBMO ALGORITHM IN NON-CONVEX ECONOMIC DISPATCH PROBLEMS

The total production cost minimization process is projected as illustrated in the conceptual model in Fig. 1. The process is started with a random number generator which is randomly generated from the conventional generating unit's output. The generated random numbers are then used in the optimization process by the HEBMO. The HEBMO algorithm will utilize the power system data and the generated random numbers or decision variables to determine the best output of the conventional generating units. At this stage, the procedure will be repeated until the HEBMO optimization process has reached a point of convergence. Simultaneously, the HEBMO will send the optimization progress of total generation cost to Power System Control Centre for deeper analysis. Any necessary modifications of the parameters can be occurred to achieve the desired output.

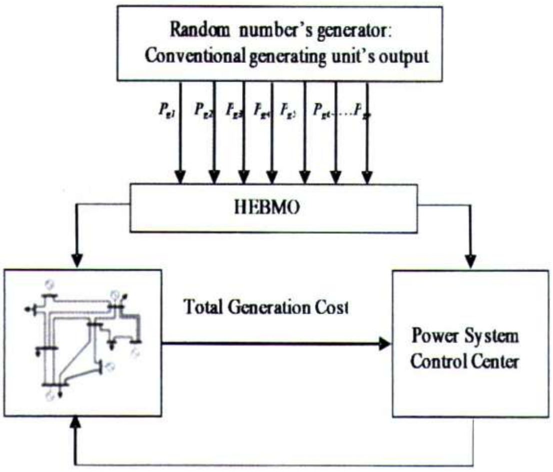

Fig.1 The proposed conceptual model of HEBMO for total generation cost minimization

Fig.2 shows the flowchart of the proposed HEBMO algorithm. HEBMO operators involved are initialization, mutation process, combination, ranking and selection, combination, and lastly convergence test. All these elements briefly discuss as follow.

Step1: Initialization

The first process is the random number generation of decision variables. For the case of IEEE 30-Bus RTS, the decision variables are P_{g1}, P_{g2}, P_{g5}, P_{g8}, P_{g11} and P_{g13}. This process also includes setting the lower and upper boundaries of the problem solved and the mating location of the barnacles.

Step 2: Mutation

In this proposed technique two types of mutation are executed, Gaussian Mutation and BMO reproduction, which is expressed as in (5) and (6) respectively.

$$X_{i+m,j} = X_{i,j} + N\left(0, b\left(X_{jmax} - X_{jmin}\right)\left(\frac{f_i}{f_{max}}\right)\right) \quad (5)$$

where $X_{(i,j)}$ is the parents, b is the search step, X_{jmax} is maximum parents, X_{jmin} is minimum parents, f_i is fitness i_{th} and f_{max} is maximum fitness. In this research, $N=20$, which is the number of candidates, and $b=0.005$.

$$X^N_{i}\_new = px^N\, barnacle\_d + qx^N\, barnacle\_m \quad (6)$$

where p is the normally distributed pseudo-random numbers between 0 and 1 and $q=(1-p)$.

Step 3: Combination I

The combination is a merging process of two offspring populations, bred using EP and BMO. This process will double the number of individuals.

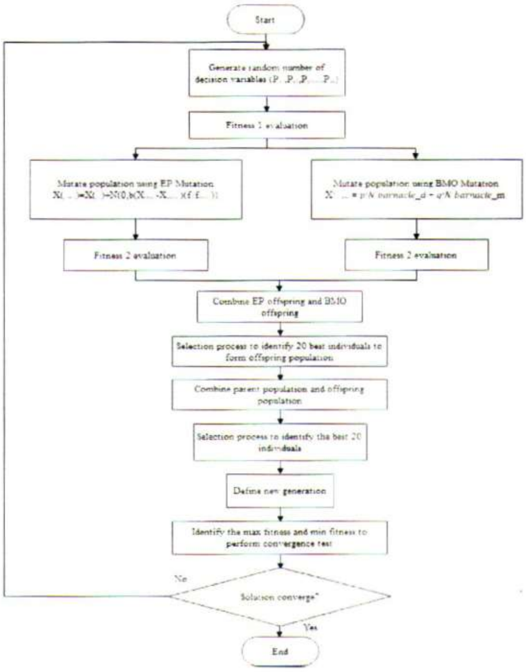

Fig.2 Flowchart of the proposed HEBMO

Step 4: Ranking and selection

Ranking and selection are two consecutive processes, conducted on the combined populations. The ranking process can simply be called elitism; sort all the individuals for all the control variables in accordance with the fitness values. It depends on the objective function whether maximization or minimization process. Subsequently, a selection process takes place which identifies the 20 individuals in the top 20 fitness values of the list. These individuals will be used for the next process.ss

Step 5: Combination II

The best 20 individuals from the previous process will be selected to recombine with 20 accepted parents that are first calculated by the fitness equation. Once again, the total population size becomes doubled.

Step 6: Next generation selection

This phase will select the individuals which are fit for the next process. Again, the survivors will be nominated by ranking them based on the best fitness value. The 20 survivors are defined as a new generation so they are preparing to be used for the next iteration until HEBMO converged.

Step 7: Convergence test

A convergence test is conducted to ensure the optimal solution is achieved. The optimization process is considered complete when they converged to the specified value. This process is indicated by the stopping criterion, formulate by the difference between the maximum and minimum fitness as in (7). The algorithm will keep repeating the same process until the solution converged.

$$fitness_{max} - fitness_{min} \leq 0.0001 \quad (7)$$

IV. RESULT AND DISCUSSION

HEBMO is assessed under two scenarios which are line and generator outages. The IEEE 30-Bus RTS and IEEE 57-Bus RTS were selected as the test systems, consisting of 6 and 7 generators respectively. The power generator limits, and cost coefficients [24], [25] for IEEE 30-Bus RTS and IEEE 57-Bus RTS are presented in Table 1 and Table 2.

TABLE I. POWER GENERATOR LIMIT AND COST COEFFICIENT FOR IEEE 30- BUS RTS

Gen.	Pg_{min}	Pg_{max}	Cost Coefficient			Valve Point Effect	
			a_i ($/h)	b_i ($/MWh)	c_i ($/MW^2h)	e_i	f_i
P_{g1}	50	200	240	7	0.007	120	0.073
P_{g2}	20	80	200	10	0.0095	50	0.032
P_{g3}	15	50	220	8.5	0.009	30	0.051
P_{g4}	10	35	200	11	0.009	25	0.026
P_{g5}	10	30	220	10.5	0.008	25	0.026
P_{g6}	12	40	190	12	0.0075	30	0.048

TABLE II. POWER GENERATOR LIMIT AND COST COEFFICIENT FOR IEEE 57-BUS RTS

Gen.	P_{min}	P_{max}	Cost Coefficient			Valve Point Effect	
			a_i ($/h)	b_i ($/MWh)	c_i ($/MW^2h)	e_i	f_i
Pg_1	0	577.88	0	20	0.0776	300	0.20
Pg_2	0	100	0	40	0.01	50	0.45
Pg_3	0	140	0	20	0.25	80	0.40
Pg_4	0	100	0	40	0.01	50	0.45
Pg_5	0	550	0	20	0.0222	250	0.35
Pg_6	0	100	0	40	0.01	50	0.45
Pg_7	0	410	0	20	0.0323	280	0.25

Tabulated results in Table III are for the non-convex ED problem with VPE under line outage scenario conducted on IEEE 30-Bus RTS. Transmission line 29-30 is designated to be disconnected in this study. When transmission line 29-30 is omitted from the simulation, the results show that EP yields the most expensive cost, which is \$/MWh 3.9931×10^3, BMO gives \$/MWh 3.9424×10^3 and HEBMO obtained the optimal solution with \$/MWh 3.9139×10^3. Overall, the simulations demonstrated that HEBMO outperformed the EP and BMO, indicated by the lowest generation cost attained. The HEBMO solves the best solutions generated by each unit are P_{g1}=179.1065 MW, P_{g2}= 20.0000 MW, P_{g5}=49.9019 MW, P_{g8}=14.8240 MW, P_{g11}=15.8600 and P_{g13}= 12.0211 MW.

TABLE III. RESULT OF NON-CONVEX ED PROBLEM WITH VPE UNDER LINE OUTAGE SCENARIO FOR IEEE 30-BUS RTS

Line P_g	**29-30**		
	EP (MW)	***BMO (MW)***	***HEBMO (MW)***
P_{g1}	180.0547	222.1421	179.1065
P_{g2}	24.0105	21.5078	20.0000
~~P_{g5}~~	27.7869	17.3843	49.9019
P_{g8}	11.5141	12.3801	14.8240
P_{g11}	25.4041	10.2080	15.8600
P_{g13}	23.6310	12.2649	12.0211
Generation Cost ($/MWh)	3.9931x10^3	3.9424x10^3	3.9139x10^3

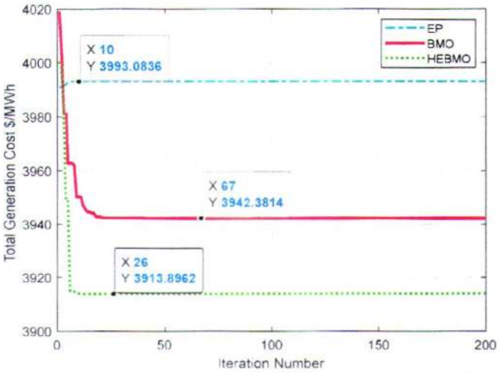

Fig.3 Convergence performance of EP, BMO and HEBMO for non-convex ED problem with VPE under line outage scenario for IEEE 30-Bus RTS

The optimization performance is depicted in Fig. 3. From the curve, the proposed technique HEBMO exhibits a fast convergence as compared to EP and BMO. HEBMO can achieve the optimal solution with the lowest generation cost within less iteration than BMO. Even though EP converged the fastest, it achieves the highest generation cost which is not desirable. This implies that the hybridization of EP and BMO, giving superior performance in terms of obtaining the lowest generation cost. When voltage imbalance occurs, either a drop or a rise due to contingencies in the power system network, this is advantageous to power system operators who can utilize optimization technique for achieving the desired optimal solution.

Table IV shows a result under generator outage for ED with VPE conducted on IEEE 30 Bus-RTS. EP, BMO, and HEBMO optimized the generation cost when generator 13 was turned off, resulting in $/MWh 3.7968x103, $/MWh 3.7303x103, and $/MWh 3.7254x103 respectively. HEBMO shows the most cost-effective technique, by demonstrating the lowest generation cost. The best solution obtained by HEBMO for the generating units in making the lowest total generation cost is P_{g1}=179.1065 MW, P_{g2}= 23.4967 MW, P_{g5}=49.9689 MW, P_{g8}=29.0418 MW, and P_{g11}=20.0000 MW.

TABLE IV. RESULT OF NON-CONVEX ED PROBLEM WITH VPE UNDER GENERATOR OUTAGE SCENARIO FOR IEEE 30-BUS RTS

Generator P_g	**13**		
	EP (MW)	***BMO (MW)***	***HEBMO (MW)***
P_{g1}	181.4843	221.8198	179.1065
P_{g2}	42.9158	20.3686	23.4967
P_{g5}	31.4388	27.0689	49.9689
P_{g8}	23.1522	13.8200	29.0418
P_{g11}	13.7824	12.3010	20.0000
P_{g13}	OFF	OFF	OFF
Generation cost ($/MWh)	3.7968x10^3	3.7303x10^3	3.7254x10^3

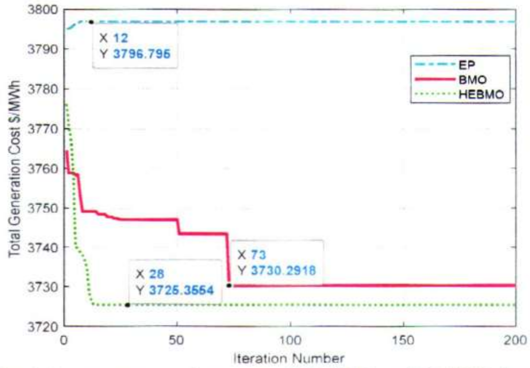

Fig. 4. Convergence performance of EP, BMO and HEBMO for non-convex ED problem with VPE under generator outage scenario for IEEE 30-Bus RTS

Fig. 4 shows the optimization performance under the generator outage scenario for IEEE 30-Bus RTS. It shows the same trend as previous, that single optimization techniques, EP and BMO lost over the hybrid algorithm, HEBMO. HEBMO managed to achieve the converged solution within less iteration number compared to BMO and achieved the lowest generation cost. EP took the least iteration number to converge but suffers due to the highest generation cost. The curves indicate that HEBMO is a powerful optimization algorithm in addressing the generator outage contingency by revealing a good optimization performance and being able to minimize the generation cost at the lowest value.

Table V presents the result of the non-convex ED problem with VPE for IEEE 57-Bus RTS under transmission line contingency. Line 28-29 were removed in this study, with EP optimizing the generation cost worth $/MWh 4.4772x104, then BMO and HEBMO lowering the cost to $/MWh 4.2827x104 and $/MWh 4.2465x104 respectively. Hence, from the presented results, it was discovered that HEBMO showing its dominance in achieving the lowest generation costs. HEBMO requires 157.4313 MW for P_{g1}, 49.1004 MW for P_{g2}, 60.6596 MW for P_{g3}, 45.1043 MW for P_{g6}, 493.0818 MW for P_{g8}, 66.0088 MW for P_{g9} and 402.1272 MW for P_{g12}.

TABLE V. RESULT OF NON-CONVEX PROBLEM WITH VPE UNDER LINE OUTAGE SCENARION FOR IEEE 57-BUS RTS

Line / P_g	28-29		
	EP (MW)	***BMO (MW)***	***HEBMO (MW)***
P_{g1}	279.8494	188.4955	157.4313
P_{g2}	8.8228	70.8368	49.1004
P_{g3}	87.9262	78.7864	60.6596
P_{g6}	26.4172	69.4625	45.1043
P_{g8}	403.8244	483.9628	493.0818
P_{g9}	79.9356	33.9780	66.0088
P_{g12}	383.3863	349.5450	402.1272
Generation Cost ($/MWh)	$4.4772\text{x}10^4$	$4.2827\text{x}10^4$	$4.2465\text{x}10^4$

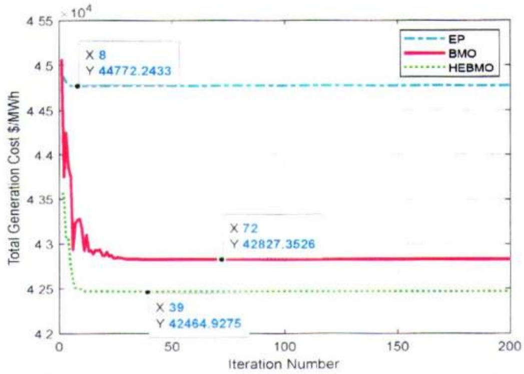

Fig.5. Convergence performance of EP, BMO and HEBMO for non-convex ED problem with VPE under line outage scenario for IEEE 57-Bus RTS

Fig.5 shows the optimization performance between EP, BMO, and HEBMO for non-convex ED problems with VPE under line outage scenario for IEEE 57-Bus RTS. Similarly, HEBMO is outstanding compared to EP and BMO as emphasized in the figure. Hence, the proposed algorithm HEBMO is a superb algorithm for handling non-convex ED problems under line outage, by providing a good advantage in terms of convergence performance and minimizing the lowest generation cost. HEBMO can be a competent optimization tool to assist the power system operators at the relevant utilities to prepare the economic generation planning when it is variations in the system load.

The tabulated result in Table VI is for the non-convex ED problem with VPE under generator outage conducted on IEEE 57-Bus RTS. When generator 2 was turned off, HEBMO managed to achieve the lowest generation cost, $/MWh 4.2354x104, instead of EP and BMO giving $/MWh 4.5994x104 and $/MWh 4.2802x104, respectively. It appears that HEBMO is excellent in generating the lowest generation cost. The best solution for power generated at each generating unit obtained by HEBMO in achieving the lowest generation is P_{g1}= 188.4956 MW, P_{g3}=54.0599 MW, P_{g6}=90.5958 MW, P_{g8}=529.6268 MW, P_{g9}=58.3228 MW, and P_{g12}=351.6552 MW.

TABLE VI. RESULT OF NON-CONVEX ED PROBLEM WITH VPE UNDER GENERATOR OUTAGE SCENARIO FOR IEEE 57-BUS RTS

Generator / P_g	2		
	EP (MW)	***BMO (MW)***	***HEBMO (MW)***
P_{g1}	318.8914	219.4591	188.4956
P_{g2}	OFF	OFF	OFF
P_{g3}	95.0411	78.9872	54.0599
P_{g6}	65.3919	54.0554	90.5958
P_{g8}	486.5889	502.5725	529.6268
P_{g9}	9.0733	62.9811	58.3228
P_{g12}	297.4189	351.7380	351.6552
Generation Cost ($/MWh)	$4.5994\text{x}10^4$	$4.2802\text{x}10^4$	$4.2354\text{x}10^4$

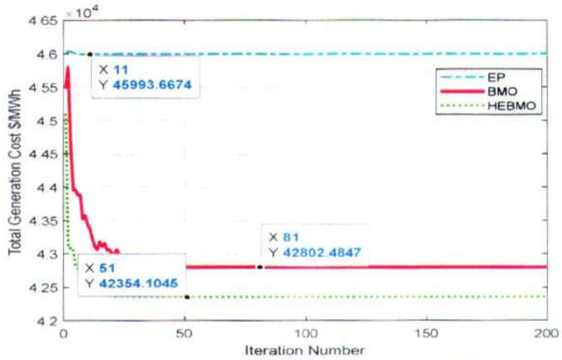

Fig.6. Convergence performance of EP, BMO and HEBMO for non-convex ED problem with VPE under generator outage scenario for IEEE 57-Bus RTS

The optimization performance of EP, BMO, and HEBMO in solving non-convex ED problem with VPE under generator outage conducted on IEEE 57 Bus-RTS is shown in Fig.6. EP achieved converged solution with the fastest convergence rate since the iteration numbers are the lowermost, but the generation cost is the highest. The iteration numbers taken by HEBMO are less than BMO, and at the same time produce the lowest generation cost. Again, this signifies an excellent HEBMO in terms of good convergence performance and the lowest generation cost in solving non-convex ED problems under generator outage.

V. CONCLUSION

This paper has presented the development of a new hybrid optimization technique termed Hybrid Evolutionary-Barnacles Mating Optimization (HEBMO) to solve non-convex ED problems with VPE validated under the line and generator outage scenarios. The proposed algorithm is tested on IEEE 30-Bus RTS and IEEE 57-Bus RTS, which consist of six and seven generating units respectively. The comparative results over two traditional single optimization techniques, EP and BMO have been conducted. The results from all the scenarios demonstrate that the proposed algorithm, HEBMO shows its superiority in achieving the optimal solution in terms of lowest generation cost, beating EP and BMO. The recently developed HEBMO optimization technique applies to other optimization problems with significant changes and modifications to the fitness and control variables. The findings from this study may be useful to utilities in performing offline corrective action when contingencies occurred.

VI. ACKNOWLEDGEMENT

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