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Solving the Economic Load Dispatch Based on NSGA-II and RNSGA-II

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Abstract- Penetration of renewable energy sources (RES) has become very crucial for replacing fossil fuel-based energy with clean energy. However, the main challenges in including RES in power systems are the uncertainty ratio in production and the intermittent nature of generation. These issues cause severe problems in system stability and security for satisfying the load requirements at a reasonable energy cost. Therefore, optimizing the unit allocated power and the total cost are the main two objectives to solve the Economic load dispatch (ELD) problem optimally for satisfying the load demand with the minimum amount of allocated power and, hence minimizing the total cost. Several optimization methods have been used in literature to solve ELD problems including multiobjective functions. However, dealing with objective functions separately causes some conflicts between them. Therefore, this paper presents a new approach to solve the ELD problem based on the non-dominated sorting genetic algorithm II (NSGA-II) and the reference point RNSGA-II. The presented method has been implemented alongside the conventional genetic algorithm (GA) for validation and comparison. Also, it is validated with the particle swarm method for comparing the performance parameters of the new method. The presented method is tested with and without losses considerations. The results showed the superiority of the proposed method as compared with other methods.

Keywords Pareto optimization, NSGA-II, RNSGA-II, Particle Swarm, Economic Load Dispatch, Renewable Energy Sources

1. Introduction

Penetration of renewable energy sources like solar photovoltaic (PV) and wind energy has been growing in power systems for replacing fossil fuel energy with clean energy to reduce greenhouse gas (GHG) emissions [1]. However, most renewable energy sources have an intermittent nature of energy production due to the dependency on the weather condition. For example, solar energy production depends on the temperature and the sun's irradiance [2]. Also, wind energy production depends on the wind speed profile [3]. In addition, the total system cost is one big consideration when sizing for renewable energy systems, for this reason many assessments of the cost are done [4]. So, optimizing the total cost and the generated energy to satisfy the load with the optimum generation are the most two criteria for optimizing renewable energy power systems. The economic load dispatch is the most common problem in a power system for allocating the optimum power generation for each unit for fulfilling the load demand and satisfying the power source constraints [5]. By allocating the units of power sources optimally, it is possible to reduce GHG emissions and minimize the operating cost and the total cost of energy. The concept of Pareto optimization can be used by any optimization method like Genetic algorithm (GA) [6], particle swarm optimization (PSO), simulated annealing (SA), ant colony optimization (ACO) [7]. Many methods have been used in the literature for solving the ELD problem. For example, particle swarms have been utilized for solving ELD optimization problems by developing a mathematical model and then applying an improved symbiosis particle swarm optimization (ISPSO) [5]. Moreover, a new method based on phasor particle swarm optimization (PPSO) has been presented for solving non-convex economic load dispatch problems [7]. In addition, surveying literature came up with a long list of many methods that have been used for solving like the particle Swarm method [8]. Grey Wolf Optimization Algorithm with multi-objective criteria including cost and environment; Newton-Raphson calculation-based method [9]; memory-based gravitational search algorithm considering the environmental and emissions constraints [10] and probability security criterion [11]. In addition, there are many other techniques used to economic power dispatch like: bidirectional global optimization technique, new stochastic techniques and heuristic search techniques. An emission constrained dynamic ELD has been presented in [12]. For example, GA has been utilized with multi-objective criteria and constraints [13]. Also, a multi-objective constraints PSO has been developed based on an improved symbiosis PSO has been used [14]. Multi-objective evolutionary algorithms have been developed and presented for solving the electric power dispatch and ELD problems [15]. To sum up the surveyed literature, many methods have been utilized for solving the ELD problem with multi-objective criteria. However, there is still a knowledge gap for reducing the power losses and the total cost of energy. Therefore, this paper presents a solution for the ELD problem based on the NSGA-II and RNSGA-II methods. The new approach has been verified with a valid PSO-based method selected from literature for verifying the results of the new method and to compare the results to determine the performance parameters of the new method [16]. The paper is organized as follows: Section 2 introduces the design and methodology of the new method, case model application is used in section 3, section 4 demonstrates and discusses the results, section 5 concludes the work.

2. Design and Methodology

Pareto optimization is the area of mathematical optimization of two or more objective functions at the same time without degrading the other functions [17]. The mathematical representation of a multi-objective criteria problem can be represented as follows:

$$\text{Min}\,\{f_1(\bar{x}), f_2(\bar{x}), f_3(\bar{x}), \dots, f_k(\bar{x})\} \tag{1}$$

S.t $\bar{x} \in X$

With $k \geq 2$ is the number of the objectives and the set X is the feasible set of vectors of decisions

Also, the vector of the objective function can be formulated as follows:

$$\vec{f}: X \xrightarrow{yields} R^k, \vec{f}(\vec{x}) = (f_1(\vec{x}), f_2(\vec{x}), \dots, f_k(\vec{x}))^T \tag{2}$$

With $\vec{x} \in X$ is a feasible solution or decision and $\vec{f}(\vec{x})$ Is called an objective. The formulation of the ELD problem is presented in the next subsections.

2.1 Objective functions

Economic and clean power generation can be realized by reducing the fuel cost and the GHG emission which can be formulated as follows:

$$F = f_{environment} + f_{fuel\_cost} \tag{3}$$

The environment objective function cost can be determined as follows:

$$f_{environment} = \min\{\sum_{i=1}^{n} A_i + B_i P_i + C_i {P_i}^2 + D_i \operatorname{Sin}(G_i P_i)\} \tag{4}$$

Where i is the ith generation unit of n generators, $A_i, B_i, C_i, D_i, and\ G_i$ Are emission coefficients of each generator like fuel type and carbon dioxide factors and P_i is the amount of generation of the ith generator. The fuel cost objective function can be formulated as follows:

$$f_{fuel\_cost} = \min\{\sum_{i=1}^{n} x_i + y_i P_i + z_i {P_i}^2\} \tag{5}$$

Where *i* is the *i*th generation unit of n generators, x, y, and z are the fuel cost coefficients of each generator like capacity, degradation, efficiency, and P_i is the amount of generation of each generator.

2.2 Constraints

The system power should be balanced so that, the generated power is sufficient to the demanded power considering 5% power losses as follows:

$$\sum_{i=1}^{n} P_i = P_D + P_l \tag{6}$$

With

$$\sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j \tag{7}$$

Where: P_i is the power generated from the i^{th} unit; P_D is the power demanded by Load; P_l is the power losses from lines and B_{ij} the line loss element between the ith and jth buses. The generated power of each unit should be within the range unit's boundaries as in Eq. (8).

$$P_{i\_min} \leq P_i \leq P_{i\_max} \tag{8}$$

3. Model Application Case Study

For testing the solution of the ELD problem, a case study model application is used. There are six generators for supplying a load of 283.4 MW considering 5% power losses at minimum fuel cost and GHG emissions with the following constraints listed in Table 1.

Table 1. The limits of power generation of the generator units

Bus number	1	2	3	4	5	6
Minimum power (MW)	50	20	15	10	10	12
Maximum power (MW)	200	80	50	35	30	40

3.1 Optimization Method Parameters

Table 2 lists the optimization parameters including the number of generations, mutation and crossover rates, population sizes, and the number of variables. The optimization parameters are selected based on trying many values and selecting the best results that reduce the convergence time and obtain the minimum cost. The developed GUI interface facilitates changing the optimization parameters for testing different scenarios.

Table 2. optimization parameters

Parameter	Variables
Variables	6
Populations	20
No of generations	100
Mutation	0.01
Crossover	0.8

3.2 Methodology

The paper presents an application of applying the Pareto optimization in solving multiobjective functions problems showing elimination of degradation effects between objective functions. The ELD problem has been selected as an example of multiobjective functions that includes the cost of fuel and total power allocated between units. This problem is selected because of the criticality of both objective functions. The total allocated power can not be less than the demand power and the total fuel cost is required to be minimized. The ELD problem has been mathematically modeled to translate the practical problem into a mathematical problem. Then the mathematical model of the problem has been solved by using one of the conventional methods which are GA and solved by NSGA-II, and R-NSGA-II as well. And ultimately the obtained results are validated with the PSO methods' results of one research work in literature. The GUI (Figure 1) facilitates changing problem parameters like the load power, the number of generators, power losses, considering the losses or not. In addition, it enables changing the optimization parameters flexibly like the number of generations, population size, mutation rate, and crossover rate.

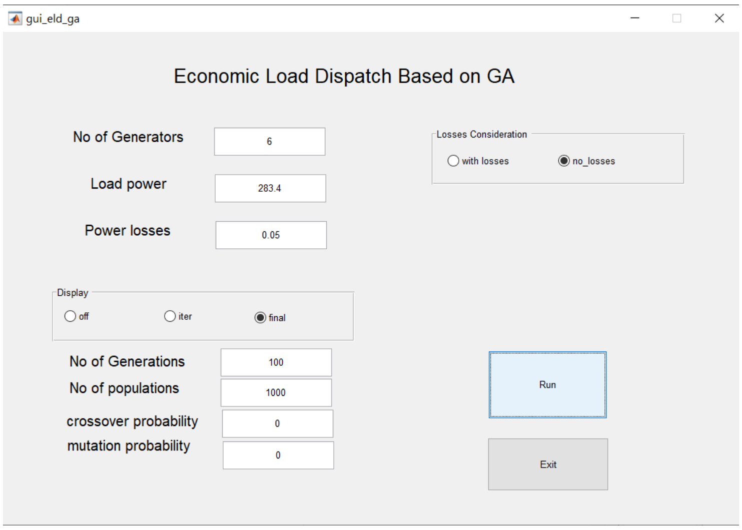

Fig. 1. The GUI interface of GA

4.Test Results and Discussion

There are six test cases for validating the three methods GA, NSGA-II, and R-NSGA-II with and without considering power losses as follows:

- NSGA-II test case without losses.
- R-NSGA-II test case without losses.
- Basic GA test case without losses.
- NSGA-II test case with losses.
- R-NSGA-II test case with losses.
- Basic GA test case with losses.

4.1 Test Results Without Losses

Table 3 lists the optimum allocated power of the six generators based on the NSGA-2, RNSGA-2, and GA methods without considering the losses. Figures 2 and 3 show all the solutions including the Pareto optimal solutions for NSGA- II and RNSGA-II. The results show the constraints have been satisfied for each generator and the demanded power by the load is satisfied. For example, comparing the minimum and maximum values of power units P1 to P6 that are listed in table 1 with the obtained results in table 3, shows clearly the allocated power is within the brackets of constraints. Also, the NSGA-II allocated total power of 283.4054 MW for satisfying the load which is lower than that obtained by the GA method which was 283.4102 MW. Tables 4 and 5 lists the determined optimum fuel cost coefficients for NSGA II and RNSGA-II respectively.

Table 3. The results of NSGA-II, RNSGA-II, and GA without losses

Methods \ Power (MW)	P1	P2	P3	P4	P5	P6	Total
NSGA- II without losses	134.893	51.4623	27.6614	14.8585	21.1394	33.3913	283.4054
RNSGA-II without losses	145.382	56.6976	21.9095	24.0043	12.1389	23.2685	283.401
GA without losses	98.7684	67.1738	37.0488	25.7354	21.864	32.8197	283.4102

Table 4. the optimum coefficients of fuel cost based on NSGA-II without losses

Fuel cost coefficient	P1	P2	P3	P4	P5	P6
X	0.3599	0.7616	0.8346	0.6192	0.5227	0.9273
Y	1.2154	1.0828	0.5862	0.366	0.4973	2.9754
Z	0.6698	0.9214	0.5805	0.4605	0.056	0.0845

Table 5. the optimum coefficients of fuel cost based on RNSGA-II without losses

Fuel cost coefficient	P1	P2	P3	P4	P5	P6
X	0.6837	0.6351	0.3664	0.3822	0.2334	0.4924
Y	2.3575	1.467	0.4525	2.6177	1.0539	1.9829
Z	0.5801	0.3768	0.5212	0.7468	0.1434	0.4725

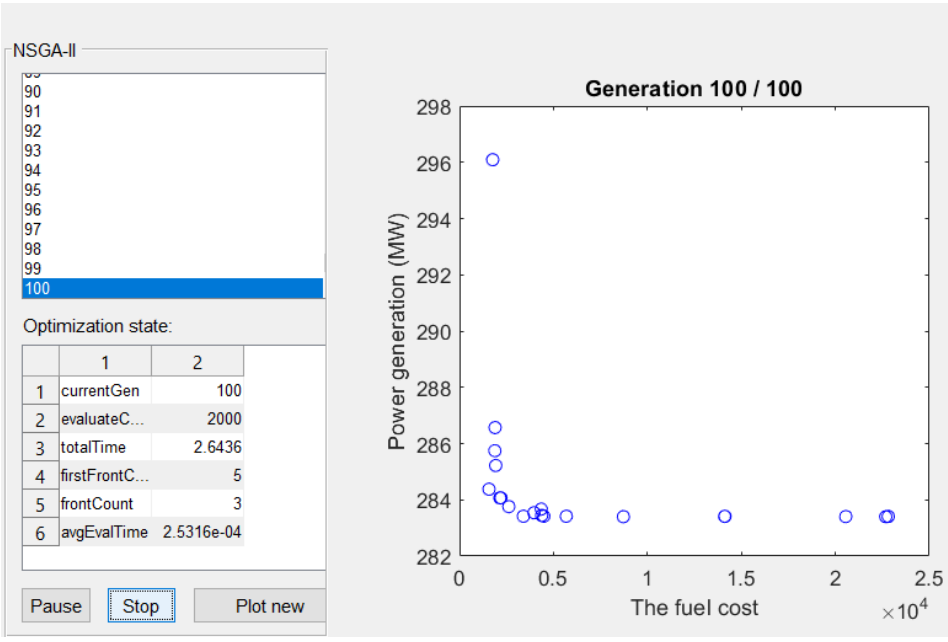

Fig. 2. The solutions of all generations including Pareto optimal solutions based on NSGA- II without losses

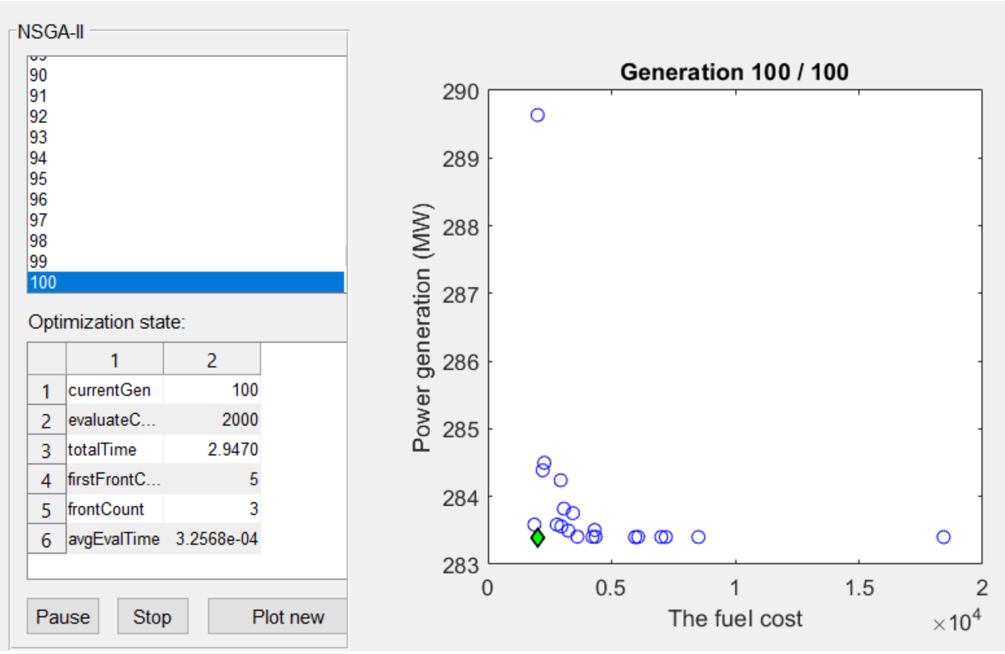

Fig. 3. The solutions of all generations including Pareto optimal solutions based on RNSGA- II without losses

Also, by using the results of [16], Table 6 compares all methods including PSO methods for cases without considering power losses showing the total fuel losses and GHG emissions. By comparing numbers that represent the total power and emission in the 8th and 9th rows for all methods, it is clear that the NSGA-II and RNSGA-II show the lowest amount of the total power allocated for satisfying the load, lowest CO2 emissions, and the lowest cost of fuel.

Table 6. comparison between all methods for cases without considering power losses

Power (MW)	PSO	CPSO*	WIPSO*	MRPSO*	GA	NSGA-II	RNSGA-II
P1	81.047	78.043	83.0324	73.0231	98.7684	134.893	145.382
P2	63.1092	63.0197	60.0947	62.1528	67.1738	51.4623	56.6976
P3	45.6863	48.632	44.023	46.8732	37.0488	27.6614	21.9095
P4	32.6824	34.0721	33.7961	34.0872	25.7354	14.8585	24.0043
P5	32.1054	27.0921	32.0823	28.4035	21.864	21.1394	12.1389
P6	28.731	32.5401	30.432	38.8732	32.8197	33.3913	23.2685
Total Power	283.361	283.399	283.460	283.413	283.41	283.405	283.401
Environmental emission (ton/h) using coefficients of in [16]	85137.02	83500.46	85265.26	79847.87	83446.91	83445.44	83444.26

* CPSO: comparative particle swarm optimization; WIPSO: weight improved particle swarm optimization; MRPSO: moderate-random-search particle swarm optimization

4.2 Test Results With Losses

Table 7 lists the optimum allocated power of the six generators based on the NSGA-II, RNSGA-II, and GA methods with considering the losses. Figures 4 and 5 list all the solutions including the Pareto optimal solutions. The results show the constraints have been satisfied for each generator and the demanded power by the load is fulfilled. For example, comparing the minimum and maximum values of power units P1 to P6 that are listed in table 1 with the obtained results in table 7, shows clearly the allocated power is within the brackets of constraints. Also, the NSGA-II allocated total power of 298.351 MW for satisfying the load which is lower than that obtained by the GA method which was 300.409 MW. The results show the constraints have been satisfied for each generator and the demanded power by the load is satisfied. Tables 8 and 9 list the determined optimum fuel cost coefficients for NSGA- II and RNSGA- II respectively in case of considering losses.

Table 7. The results of NSGA- II, RNSGA- II, GA with losses

	P1	P2	P3	P4	P5	P6	Total
NSGA- II with losses	163.16	37.8459	37.1193	21.1579	15.3922	23.676	298.351
RNSGA- II with losses	137.578	67.5818	36.5559	20.6333	12.4606	23.8801	298.69
GA with losses	147.03	48.2349	34.1558	21.8381	22.59	26.5603	300.409

Table 8. the optimum coefficients of fuel cost based on NSGA- II with losses

Fuel cost coefficient	P1	P2	P3	P4	P5	P6
X	0.6076	0.9196	0.6227	0.8685	0.7119	0.2167
Y	2.0889	1.2222	1.518	2.9073	0.5402	2.8885
Z	0.9313	0.6475	0.9054	0.0904	0.4877	0.9894

Table 9. the optimum coefficients of fuel cost based on RNSGA- II with losses

Fuel cost coefficient	P1	P2	P3	P4	P5	P6
X	0.2605	0.1648	0.9391	0.985	0.0054	0.9976
Y	1.0214	0.8184	2.3984	1.5343	2.6828	2.9228
Z	0.7935	0.3823	0.5567	0.9692	0.2193	0.5984

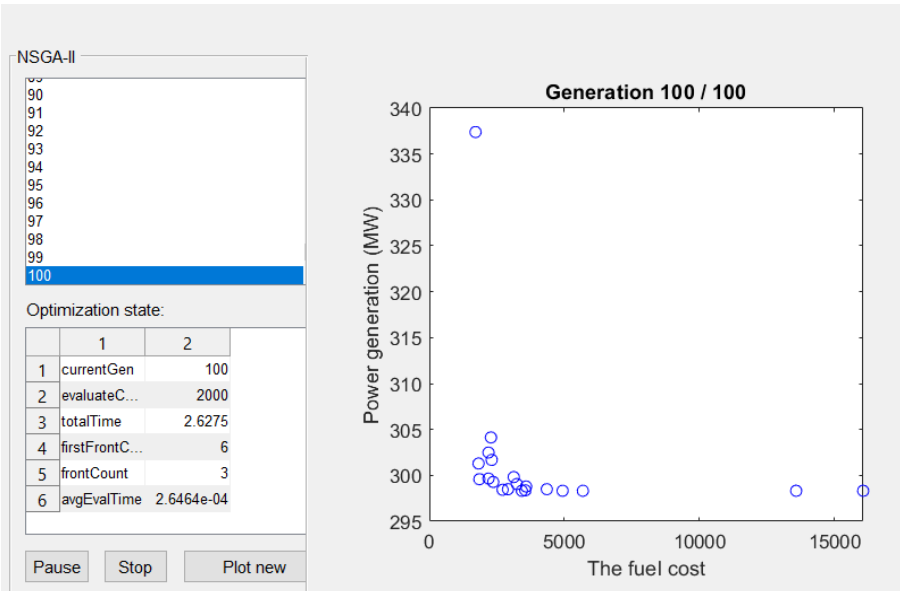

Fig. 4. The solutions of all generations including Pareto optimal solutions based on NSGA- II with losses.

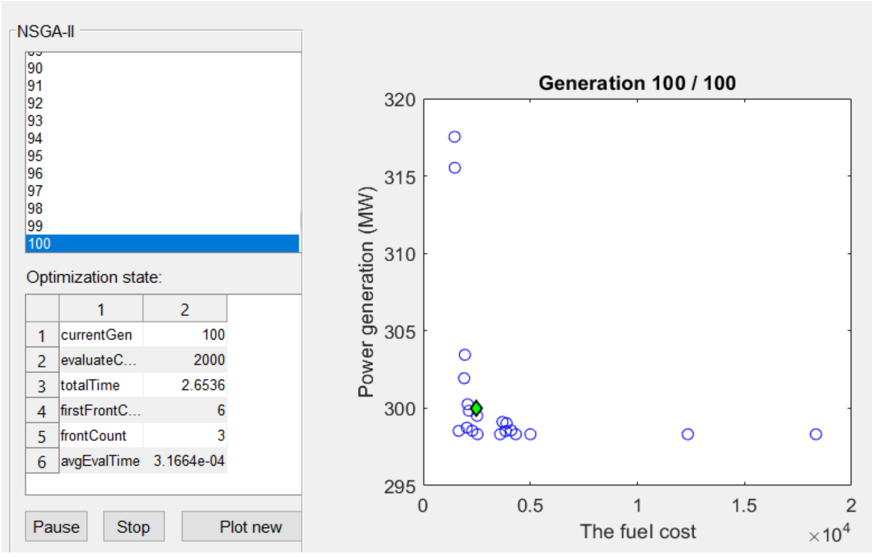

Fig. 5. The solutions of all generations including Pareto optimal solutions based on RNSGA- II with losses

Also, Table 10 compares all methods including PSO methods for cases with considering power losses showing the total fuel losses and GHG emissions. By comparing numbers that represent the total power and emissions in the 9th and 10th rows for all methods, it is clear that the NSGA-II and RNSGA-II show the lowest amount of the total power allocated for satisfying the load, lowest CO2 emissions, and the lowest cost of fuel.

Table10. Comparison between all methods for cases with considering power losses

Power (MW)	PSO	CPSO	WIPSO	MRPSO	GA	NSGA-II	RNSGA-II
P1	147.03	146.034	147.581	145.7801	147.03	163.1597	137.5782
P2	43.114	46.0732	46.889	43.0912	48.2349	37.84587	67.58184
P3	36.661	34.0742	47.0705	43.07654	34.1558	37.11932	36.55594
P4	23.019	26.0198	16.7863	24.0763	21.8381	21.15791	20.63332
P5	25.377	24.108	24.7219	23.1732	22.59	15.39223	12.46057
P6	27.632	26.0911	19.8925	23.0453	26.5603	23.67595	23.88008
Losses	19.435	19.0003	19.5407	18.8468	17.0089	14.951	15.29
Total	302.835	302.400	302.9407	302.2468	300.4089	298.351	298.69
Environmental emission (ton/h)	164018.7	16256.3	168090.8	162466	127672.3	191069.4	158206.7

Table11. Environmental emission coefficients

Generator	A	B	C	D	G
P1	4.091	-5.554	6.490	0.0002	2.857
P2	2.543	-6.047	5.638	0.0005	3.333
P3	4.258	-5.094	4.586	0.000001	8
P4	5.426	-3.556	3.380	0.002	2
P5	4.258	-5.094	4.586	0.000001	8

P6	6.131	-5.555	5.151	0.00001	6.667

5. Conclusion

Pareto optimization is highly recommended for optimizing multiobjective functions problems without mutual degradation effects between objective functions. So, this paper applied the Pareto optimization concept for solving the Economic load dispatch problem based on NSGA-II and RNSGA-II methods. Also, Implementation results of the basic GA method have been compared to show the performance parameters of the proposed method in optimizing the power unit allocation for minimizing fuel cost and GHG emission. All methods have been tested at the same values of parameters and conditions and validated with one published paper in the literature that used PSO methods. The test cases included with and without considering power losses. The obtained results showed significant superiority of the NSGA-II and RNSGA-II thanks to applying the Pareto optimization multi-objective method. The proposed method showed the best results in terms of the least fuel cost and GHG emission, then the basic GA method came the next best method. In a conclusion, all GA methods are better than PSO methods for this problem with the same parameters and conditions. The NSGA-II and R-NSGA-II methods validated the Pareto optimization concepts and showed successfully that they can optimize multi-objective criteria without degrading each other.

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