Hybrid method for achieving Pareto front on economic emission dispatch

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ABSTRACT
In this paper hybrid method, Modified Nondominated Sorted Genetic Algorithm (MNSGA-II) and Modified Population Variant Differential Evolution (MPVDE) have been placed in effect in achieving the best optimal solution of Multiobjective economic emission load dispatch optimization problem. In this technique latter, one is used to enforce the assigned percent of the population and the remaining with the former one. To overcome the premature convergence in an optimization problem diversity preserving operator is employed, from the tradeoff curve the best optimal solution is predicted using fuzzy set theory. This methodology validated on IEEE 30 bus test system with six generators, IEEE 118 bus test system with fourteen generators and with a forty generators test system. The solutions dissimilitude with the existing metaheuristic methods like Strength Pareto Evolutionary Algorithm-II, Multiobjective differential evolution, Multi-objective Particle Swarm optimization, Fuzzy clustering particle swarm optimization, Nondominated sorting genetic algorithm-II.

Keywords: Cost function Economic load dispatch Multiobjective function Tradeoff curve

1. INTRODUCTION
In a common parlance of power systems multiobjective economic emission load dispatch is an optimization problem which concerns with incompatible objectives like cost and emission. Best power generation with minimum emission is the desired task which leads to the optimization problem with many constraints. Power generation with optimum incremental fuel cost can be compatible with the allocation of generators in the thermal plant. The vast use of combustible fossil fuels in thermal plants produces harmful gases like CO, NO₂, SO₂ leading to contamination of atmosphere which is a major issue from a global warming perspective. With the awareness of gaseous pollutant, the United States has passed a Clean Air Act Amendments of 1990 [1] has made enforcement to all the power plants to follow the strategies to minimize the emissions from the thermal power plant. The incorporation of emission objective with Economic Dispatch (ED) problem has become a multiobjective with its complexity. Many techniques were developed for the solution of multiobjective nonlinear problems one of the possible things to convert multiobjective to mono objective. Linear Programming technique [2] considered as a single objective with a lot of assumptions and doesn’t provide the easy solution. Another approach [3] conversion of multiobjective to mono objective is implemented by using suitable weights and drawbacks associated with this one it requires multiple runs to achieve the trade-off curve, to compensate this ε constraint method was developed [4] considering another objective as a constraint with its limitation of ε levels, but this is a time consuming with the process of weak non dominated solutions. Later a novel fuzzy optimization technique [5] was applied but due to lack of composition in directing the search towards the trade-off curve which is not preferred one. A fuzzy
satisfaction maximizing decision making [6] approach implemented satisfactorily but the extension of objectives has become a tedious process. A novel approach introduced in [7] which is a formidable and exhibiting untimely convergence characteristic.

Recent development tends towards Evolutionary Algorithms (EA) for solving EELD problems compensating the downside of the classical methods to obtain Pareto set. These algorithms are based on the population which generates optimal solution on a single run having its own merits. Nondominated sorting Genetic Algorithm [8] is applied which exhibited the suboptimal solution of result and consuming more time for the evaluation. NSGA-II [9] exhibits elitism, ranking but fails in its uniformity of the trade-off, and this can be compensated using dynamic crowding distance and more MOEAs are Strength Pareto Evolutionary Algorithm [10], Niched pareto genetic algorithm [11], Multiobjective Particle swarm optimization [12], Multiobjective 0-Particle swarm optimization [13], Multiobjective Differential Evolution [14], semidefinite Programming [15], self adaptive learning bat algorithm [16], Multiobjective Global Best Artificial Bee Colony [17], Grey Wolf Optimization [18]. In an MOEA a set of solutions are obtained, which utilizes the fuzzy set theory to achieve the best compromise solution [19]. In this paper, two objectives are considered simultaneously without converting to a single objective and layouted with modification of NSGA-II and PVDE.

Combining two or more algorithms are referred to as hybridization which is a successful one in solving environmental economic load dispatch problem. The main task of the hybrid method is to provide diversified Pareto front. In this paper a hybrid method where used with the combination of MPVDE and MNSGA-II is employed which is at the initial stage half of the population is applied with MNSGA-II where non-dominated sorting is implemented and the remaining half of the population is carried with refreshed population concept of semi-interquartile range and midquartile range to eliminate immovable local optima using MPVDE and finally, Euclidean distance is evaluated for the next generation of the population. This hybrid method is tested on IEEE 30 bus system with six generators and IEEE 118 bus system with fourteen generators and 40 generators system. The remainder of the paper is organized as follows: in section 2, the mathematical formulation of EELD, in section 3 on multiobjective formulation and in section 4 on the brief description on MNSGA-II and MPVDE and hybrid method is presented in section 5 results of three test cases showing better performance in comparison with existing methods is presented.

2. PROBLEM FORMULATION

The combined economic emission dispatch is incorporated with two contradictory objectives, cost and emission with constraints. The quadratic equation related to the cost function of every individual power generation unit is given as

\[ C = \sum_{k=1}^{n} F_k(P_{Gk}) \]  

(1)

\[ F_k(P_{Gk}) = (a_k + b_kP_{Gk} + c_kP_{Gk}^2) \]  

(2)

where \( F_k(P_{Gk}) \) is \( k^{th} \) generator cost function. The \( a_k, b_k, \) and \( c_k \) are referred to \( k^{th} \) unit fuel cost coefficients. \( n \) is the no. of generators. \( C \) is the total fuel cost in dollars per hour. The below (3) is a combination of quadratic and exponential functions represents the emission levels of which all harmful toxic gases.

\[ E(P_{Gk}) = \sum_{k=1}^{n} \left( (\alpha_k + \beta_kP_{Gk} + \gamma_kP_{Gk}^2) + \xi_k\exp(\lambda_kP_{Gk}) \right) \]  

(3)

where \( \alpha_k, \beta_k, \gamma_k, \xi_k, \lambda_k \) are the emission coefficient of \( k^{th} \) unit. The constraints are explained in the following.

2.1. Power balance equations

The Power balance equation is represented in (4)

\[ \sum_{k=1}^{n} P_{Gk} = P_D + P_{LOSS} \]  

(4)

here, \( P_{Gk}, P_D, \) and \( P_{LOSS} \) are represented the real power output at \( k^{th} \) generator, total load demand and power losses in transmission line respectively. The power loss is approximately calculated using (5).

\[ P_{LOSS} = \sum_{l=1}^{n} \sum_{k=1}^{n} P_{Gk}B_{lk}P_{Gk} + \sum_{k=1}^{n} P_{Gk}B_{ko} + B_{oo} \]  

(5)

where, \( B_{lk}, B_{ko}, B_{oo} \) are powerloss coefficients or B coefficients.
2.2. Power capacity limits constraints

\[ P_{G_k\text{min}} \leq P_{G_k} \leq P_{G_k\text{max}} \]  

(6)

where \( P_{G_k\text{max}} \) and \( P_{G_k\text{min}} \) are the maximum and minimum values of output power at the \( k^{th} \) generator.

2.3. Valve point effect of cost function

With the incorporation of these effects in the linear problem of optimization is transfigured to a non convex problem with cost function including the ripple curve. The modified quadratic equation with these effects is represented in (7).

\[ F_k(P_{G_k}) = a_k + b_kP_{G_k} + c_kP_{G_k}^2 + |e_k\sin(f_k(P_{G_k\text{min}} - P_{G_k}))| \]  

(7)

3. EVOLUTIONARY ALGORITHMS

Evolutionary algorithms overcome the drawbacks associated with classical methods. In this paper, a hybrid method implemented to achieve efficient, good diversity and faster convergence rate.

3.1. Modified NSGA-II

In MNSGA-II the Euclidean distance is implemented in the selection process of each front in 2N Population of the combined parent and offspring population. Euclidean distance implements midpoints to enhance the diversity in each front. Population members which are out of the range of Euclidean distance will be discarded and rest include in Population N, during the selection process, selected members \( N_i \) exceeds the N then best fitness members are selected, and if the selected population is less than N, a new population is generated which is within Euclidean distance.

\[ \text{Euclidean distance } D_{a,b}^i = \frac{\sqrt{\sum_{m=1}^{N}(d_m^a - d_m^b)^2}}{(n-1)} \quad ; \quad i=1, 2, 3...... \]  

(8)

If \( N_i > N \) then best fitness population members selected.
If \( N_i < N \) then new random population is generated which should lie in the range of Euclidean distance.

The range of Euclidean distance is developed as \((D_{a,b}^i + D_o, D_{a,b}^i - D_o)\), where \( D_o \) is selected such that the maximum population members should exist within the range of Euclidean distance, the application of Euclidean distance is to enhance the diversity among the population members.

3.2. Modified population variant differential evolutionary algorithm

In PVDE [20] the initial population is refreshed using the interquartile range concept at the initial stage to make an efficient algorithm. Scaling factor and crossover probability variation, place a vital role in the production of offspring. In MPVDE the concept coefficient of Quartile deviation is used.

**Step 1:** The initial half random population is generated.

**Step 2:** A two row vector is initialized for scaling factor and crossover probability parameters in the range \([0,1]\) and it minimum size is \([1x3]\) vectors. Evaluation of maximum, minimum and median values for each parameter is determined.

**Step 3:**

- Initially vector difference \( \text{Var}_{\text{max}} \) is evaluated with generation limits its difference is multiplied with 0.01.
- \( \text{Var} \) is calculated using the concept of coefficient of Quartile deviation with each column of parent population.

\[ \text{Var} = \frac{Q_1 - Q_2}{Q_1 + Q_2} ; \]  

(9)

where \( Q_1 \) is the semi interquartile range and \( Q_2 \) is the mid quartile range

\[ Q_1 = \frac{\text{High quartile} - \text{Low quartile}}{2} ; \]  

(10)

\[ Q_2 = \frac{\text{High quartile} + \text{Low quartile}}{2} ; \]  

(11)

- With new limits of Lower and Higher new refreshment population is evaluated with step 1.
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3.3. Hybrid method

In this paper the combination of MNSGA-II and MPVDE is used as a hybrid method for solving environmental economic load dispatch with two objectives cost and emission. In PVDE [20] two objectives are converted into mono objective using the weighted sum method but in this paper cost function and emission function is considered as two objectives. In this paper the entire population is split into two half’s, the first half of the population is applied with MNSGA-II and second half of the population is encountered by MPVDE to achieve the best optimal solution the steps in the application of MNSGA-II and MPVDE for solving environmental economic load dispatch is as follows

- Initialize the number of objectives, decision variables, and load demand, maximum number of iterations and also cost and emission coefficients. Let \( k = [k_1, k_2, k_3, k_4, k_5, \ldots] \) where \( k \) is the decision vector and each element corresponds to the output power of each generator.
- Generate the random population such that it has to satisfy equality constraint in (4).
- MNSGA-II is applied for the first part of the initial population and using (2) and (3) evaluate the objective function of both cost and emission.
- From the existing population initially identify the nondominated individuals. Predict the nondominated sorting such that the ranking selection method is implemented to highlight the ranking fronts.
- For the evaluation of crowding distance, a sorted population of each objective function value in the increasing order is required.
- The generation of half of the initial population of the offspring is evaluated by performing the mutation and crossover.
- Evaluate the objective functions from (2) and (3) for the next half of the population using MPVDE, for this population refreshment is done by using the concept of semi interquartile and mid quartile.
- Predicting the best population which gives minimum cost value and performs the crossover and mutation for the generation of offspring.
- Merge both the offsprings that will equalise to the population in number. Combine parent population and offspring that leads to twice the population.
- Select the best individuals of population based on euclidean distance such that the best non-dominant one placed in the repository. In the next iteration it is taken as a new parent population and the process repeats until it reaches maximum generation. Generally in the multiobjective combined environmental economic load dispatch solutions leads to multiple optimal points in which the best optimal is to be obtained, for this purpose a fuzzy set theory [21] is implemented.

3.4. Best optimal value

Fuzzy set theory is helpful in achieving the best solution from the pareto optimal set for the decision maker [22], decision maker decision is inaccurate in nature. \( k^{th} \) objective function of the solution in pareto set \( F_k \) is indicated by a membership function \( \mu_k \) is defined as

\[
\mu_k = \begin{cases} 
1, & F_k \leq F_k^{\text{min}} \\
\frac{F_k^{\text{max}} - F_k}{F_k^{\text{max}} - F_k^{\text{min}}}, & F_k^{\text{min}} < F_k < F_k^{\text{max}} \\
0, & F_k \geq F_k^{\text{max}} 
\end{cases}
\]  

(12)

where \( F_k^{\text{min}} \) and \( F_k^{\text{max}} \) are the minimum and maximum values of \( k^{th} \) objective function, the normalized membership function \( \mu_i \)

\[
\mu_i = \frac{\sum_{k=1}^{N_{\text{obj}}} \mu_k}{\sum_{j=1}^{M} \sum_{k=1}^{N_{\text{obj}}} \mu_k}
\]  

(13)

Nondominated solutions in number is represented as \( M \), the best solution having maximum value of \( \mu_i \).
4. RESULTS AND DISCUSSION

This hybrid method is tested with three test cases. Case 1 related to IEEE 30 bus test system with six generators with and without losses and Case 2 applied to IEEE 118 bus test system with 14 generators with and without valve point loading effect and Case 3 is implemented on a 40 generators system without losses. In all the cases cost and emission objective function are not converted into a single objective and not considered as a constraint in the optimization problem. MATLAB program was developed on Intel i3 processor with 2GB RAM, an operating system is Windows 10.

4.1. Case 1

IEEE 30 bus test system having a load demand of 2.834pu with a base of 100MVA and having Population number 40 and the maximum no of iterations is 100. The tradeoff curve for the EELD without losses is shown in Figure 1 and with losses is shown in Figure 2. The minimum fuel cost of 607.1265 ($/hr) is achieved for the emission of 0.2031 (ton/hr) and the maximum fuel cost of 637.8721($/hr) with the minimum emission of 0.1942(ton/hr) as shown in Table 1 the execution time taken without losses is 9.2020 sec and with the losses the lowest cost value is 614.2687 ($/hr) for the emission value of 0.2009 (ton/hr) is shown in Table 2 and the time taken for the computation is 9.840sec. The cost and emission coefficients as well as maximum and minimum values of power generation is taken as in [23].

![Figure 2. IEEE 30 bus test system with losses](image_url)

**Table 1. Comparison of cost and emission results of case 1 without losses**

| Method          | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) |
|-----------------|----------|-------------------|----------|-------------------|----------|-------------------|----------|-------------------|----------|-------------------|
| MNMNSGA-II+MPVDE | 0.2227   | 0.4076            | 0.1097   | 0.4086            | 0.1162   | 0.4151            | 0.1194   | 0.3979            | 0.1070   | 0.4097            |
| PG1             | 0.3719   | 0.2933            | 0.5859   | 0.5245            | 0.5060   | 0.5298            | 0.5212   | 0.5336            | 0.5300   | 0.5348            |
| PG2             | 0.3719   | 0.2933            | 0.5859   | 0.5245            | 0.5060   | 0.5298            | 0.5212   | 0.5336            | 0.5300   | 0.5348            |
| PG3             | 0.7362   | 0.3892            | 0.10162  | 0.3834            | 1.0098   | 0.3808            | 1.0041   | 0.3984            | 1.0150   | 0.3842            |
| PG4             | 0.5247   | 0.5307            | 0.5245   | 0.5378            | 0.5060   | 0.5298            | 0.5212   | 0.5336            | 0.5300   | 0.5348            |
| PG5             | 0.4196   | 0.5076            | 0.3598   | 0.5101            | 0.3550   | 0.5070            | 0.3914   | 0.5515            | 0.3673   | 0.5140            |
| PG6             | 0.4196   | 0.5076            | 0.3598   | 0.5101            | 0.3550   | 0.5070            | 0.3914   | 0.5515            | 0.3673   | 0.5140            |
| Cost            | 607.1265 | 637.8721          | 600.132  | 638.264           | 600.2071 | 638.9388          | 600.2823 | 636.9045          | 600.132  | 638.358           |
| Emission        | 0.2031   | 0.1942            | 0.2222   | 0.1942            | 0.2219   | 0.1942            | 0.2205   | 0.1944            | 0.2222   | 0.1942            |

**Table 2. Comparison of cost and emission results of case 1 with losses**

| Method          | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) | Cost     | Emission (ton/hr) |
|-----------------|----------|-------------------|----------|-------------------|----------|-------------------|----------|-------------------|----------|-------------------|
| MNMNSGA-II+MPVDE | 0.2606   | 0.4048            | 0.1189   | 0.4107            | 0.1318   | 0.4169            | 0.1145   | 0.3872            | 0.1130   | 0.4063            |
| PG1             | 0.4012   | 0.4625            | 0.3085   | 0.4635            | 0.2925   | 0.4478            | 0.3240   | 0.4209            | 0.3145   | 0.4586            |
| PG2             | 0.4012   | 0.4625            | 0.3085   | 0.4635            | 0.2925   | 0.4478            | 0.3240   | 0.4209            | 0.3145   | 0.4586            |
| PG3             | 0.5391   | 0.5436            | 0.5200   | 0.5447            | 0.5287   | 0.5488            | 0.5086   | 0.5271            | 0.5826   | 0.5510            |
| PG4             | 0.7042   | 0.4110            | 1.0081   | 0.3903            | 0.9934   | 0.3847            | 1.0525   | 0.4545            | 0.9860   | 0.4084            |
| PG5             | 0.5310   | 0.5380            | 0.5286   | 0.5444            | 0.5362   | 0.5635            | 0.5488   | 0.5950            | 0.5264   | 0.5432            |
| PG6             | 0.4180   | 0.4942            | 0.3742   | 0.5155            | 0.3786   | 0.4995            | 0.3191   | 0.4828            | 0.350    | 0.4974            |
| Cost            | 614.2687 | 640.2599          | 605.548  | 646.190           | 606.276  | 644.1750          | 607.8919 | 637.6409          | 607.786  | 642.896           |
| Emission        | 0.2009   | 0.1942            | 0.2208   | 0.1942            | 0.2197   | 0.1942            | 0.2247   | 0.1947            | 0.2201   | 0.1942            |
4.2. Case 2

It is implemented on IEEE 118 bus system with 14 generators with and without Valve point loading effect is exhibited. Total Demand was 2000MW [25] with a population of 40 and crossover probability and mutation values are 0.85 and 0.166. Comparison is shown in Table 3 without valve point loading effect and in Table 4 with valve point loading the corresponding Pareto optimal solutions are shown in Figure 3 and Figure 4. For a minimum emission of 2776.1633(ton/hr) the cost value is 8968.1794($/hr) is obtained having the execution time of 9.906sec in case of without valve point and with valve point minimum emission 2754.2895(ton/hr) and related cost value is 9004.3651($/hr) with execution time of 10.572sec.

![Figure 3. IEEE 118 bus test system without valve point](image)

![Figure 4. IEEE 118 bus test system with valve point](image)

Table 3. Comparison of cost and emission results of case 2 without valve point

| Method | Cost | Emission |
|--------|------|----------|
| MNSGA-MPVE | 284.052875019457 | 197.626370894082 |
| SPEA2 | 329.7295 | 236.8771 |
| MODE | 240.0744 | 159.9989 |
| MOPSO | 325.8810125 | 250.0010 |
| FCPSO | 219.0736 | 184.3040 |

| Cost | 8786.2088315179 | 9004.36512511877 |
| Emission | 3212.807144275 | 2754.28951669385 |

Table 4. Comparison of cost and emission results of case 2 with valve point

| Method | Cost | Emission |
|--------|------|----------|
| MNSGA-MPVE | 284.052875019457 | 197.626370894082 |
| SPEA2 | 329.7295 | 236.8771 |
| NSGA-II | 935.3337 | 129.1020 |
| MOPSO | 76.8090 | 79.79355 |
| FCPSO | 69.4093 | 79.35395 |

| Cost | 8786.2088315179 | 9004.36512511877 |
| Emission | 3212.807144275 | 2754.28951669385 |
4.3. Case 3

The proposed method is applied to the 40 generators system and the results are shown in the Table 5 and the corresponding Pareto graph is shown in Figure 5 showing the best compromise solution. The total demand was 10500MW [26] with the population of 40 exhibited with 100 iterations and the trade off curve is obtained for the trials of 30 times and for the minimum emission value 112444.1310 (ton/hr) the achieved cost value 124483.5238 ($/hr) and the time taken for the execution of the Matlab program is 17.233 sec. Figure 6 shows the graph between best values from refreshed population verses number of iterations. From the graph, it is predicted that the best value of the cost function value over iteration 100 reaches the minimum cost value which is used for mutation and crossover evaluation in MPVDE. The flow chart shown in Figure 7 gives the major steps in the implementation of a hybrid method for solving economic emission dispatch problem. Initially modified non-dominant sorting genetic algorithm –I is applied followed by modified Population Variant Differential Evolution and in both the methods non-dominant sorting is applied for the generation of offspring’s and in this stream elitism concept is attributed to make the best one in the repository which enhances the convergence rate. The selection process is ordered by the crowding distance operator for improving the uniform spread over trade off curve. In MNSGA-II simulated binary crossover and the polynomial mutation is carried over for the generation of corresponding of offspring’s and the latter method MPVDE best value which produce minimum fitness is predicted among the refreshed population which is used in the calculations of mutation and crossover and generating a trust worthy results.

| Method | Unit | Cost | Emission | MNSGA-II + MPVDE | Cost | Emission |
|--------|------|------|----------|------------------|------|----------|
| PG1    | 112.591217758152 | 103.149113447733 | 465.70935396319 |
| PG2    | 113  | 106.916479663274 | 450.89985272927 |
| PG3    | 119  | 115.20494222967 | 475.842309302858 |
| PG4    | 185.93392542511 | 163.63639629782 | 487.304987512046 |
| PG5    | 97   | 533.525235230105 | 452.236324840282 |
| PG6    | 132.72290130973 | 133.97743775262 | 441.114781162747 |
| PG7    | 300  | 289.463756018975 | 39.655464963563 |
| PG8    | 300  | 297.274612619789 | 14.112493106588 |
| PG9    | 300  | 267.870157819963 | 26.455709675385 |
| PG10   | 185.670710236017 | 272.38572216004 | 92.8364973358 |
| PG11   | 101.399854667174 | 243.910619018213 | 101.54694283624 |
| PG12   | 128.99684988898  | 283.50290983938 | 169.83457470498 |
| PG13   | 125  | 370.647321748841 | 178.659794824307 |
| PG14   | 244.159417496869 | 427.208944115737 | 184.972526053006 |
| PG15   | 276.536731783833 | 379.776496078575 | 193.486955182649 |
| PG16   | 426.349359613756 | 394.23673739718 | 188.995222780554 |
| PG17   | 480.68436526678 | 409.90548362534 | 99.72223025773 |
| PG18   | 500  | 421.956960032622 | 100.394493141124 |
| PG19   | 474.512320266035 | 472.38651465806 | 102.819750031863 |
| PG20   | 500  | 473.661327061807 | 437.585726229166 |

Table 5. Cost and emission results of case 3

Figure 5. 40 generators system with no losses

Figure 6. Best value verses no of iterations
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5. CONCLUSION

The multiobjective economic emission load dispatch optimization problem has been solved with many heuristic and novel methods. In this paper, two conflicting objectives are considered simultaneously and the combination of MNSGA-II and MPVDE is highlighted as one of the hybrid methods in achieving the best optimal solution. It is tested on IEEE 30 bus test system with 6 generators and IEEE 118 bus test system with 14 generators and with standard 40 generators system. The results obtained are compared with the existing methods. In all the three test cases population parameter and the maximum number of iterations 100 remain same in achieving the Pareto optimal set. Many numbers of trails of about 30 were implemented for all methods like SPEA-II, MOPSO, and MODE, for achieving the optimal solution among this Hybrid method achieved the best optimal solution with good convergence.

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