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Generation rescheduling using multiobjective bilevel optimization

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Abstract: This paper presents a new multiobjective optimization method that can be used for generation rescheduling in power systems. Generation rescheduling in restructured power systems is performed by the system operator for different operations like congestion management, day-ahead scheduling, and preventive maintenance. The nonlinear nature of the equations involved and the constraints on decision variables pose a challenge to find the global optimum. In order to find the global optimum using a genetic algorithm, a bilevel optimization method is proposed. In the proposed multiobjective optimization method, the objectives are classified as primary and secondary based on their relative importance. The best solution is found using the secondary objective from the acceptable solutions of the Pareto-optimal front in the primary objective plane. As the financial feasibility and adherence to emission limits are of higher importance, the primary objectives considered are minimization of generation cost and emission. The secondary objective considered is reliability, to find the most reliable solution from the set satisfying the primary objectives. The proposed technique is validated on the IEEE 30-bus system and the results are presented.

Key words: Generation rescheduling, multiobjective optimization, power system reliability, genetic algorithm

1. Introduction

Generation rescheduling is a crucial activity of system operators in the context of restructured power systems. It is used for day-ahead scheduling, congestion management, and preventive maintenance. Congestion of electric power transmission networks due to overload or contingencies also necessitates the independent system operator (ISO) to alleviate it using different financial and technical measures [1]. Generation rescheduling, load shedding, and demand response are used to solve congestion problems in transmission systems [2]. The coordination process between generating companies and ISOs was discussed in [3].

Optimal power flow is used by the ISO for operations and planning. Depending on the time available for decision-making, different methods are used for solving optimal power flow. A computationally simple method based on sensitivities for congestion management was proposed in [4]. Heuristic optimization techniques like evolutionary algorithms are effective in solving multiobjective power system optimization problems that are nonlinear in nature [1, 2]. A fuzzy min-max approach was used in [2] to find the best solution in the Pareto-optimal set. A multiobjective-based evolutionary algorithm was used for reactive power optimization in [5]. An artificial bee colony algorithm was used for solving a multiobjective unit commitment problem with reliability function in [6].

From the literature survey, it is observed that risk evaluation with bilevel optimization is seldom used in power system operation and this paper partially fills the gap. A novel multiobjective genetic algorithm

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considering forced outage rate (FOR) [7] of generating stations is proposed in this paper, which can be used by an ISO for day-ahead scheduling and preventive maintenance. A new reliability index, aggregate forced outage rate (AFOR), has been introduced to find the most reliable solution among the available solutions on the Pareto-optimal front [8] of the optimization curve. The advantage of using this algorithm is that the system operator can reduce the chance of outage, as more power is scheduled on a generator unit with higher reliability.

The remainder of the paper is organized as follows. Section 2 focuses on the problem formulation. Section 3 addresses the constraints that should be considered while solving the optimization problem. Section 4 describes the proposed methodology to solve the multiobjective optimization problem. Section 5 discusses the results of simulation and, finally, Section 6 presents the conclusions and contributions of the paper.

2. Problem formulation

The considered primary objectives of generation rescheduling are minimization of generation cost ($/h) and minimization of emission (lb/h). As these two objectives conflict with each other, simultaneous optimization of both the objectives leads to a Pareto-optimal set of solutions and one among them is chosen with higher knowledge. The different objectives and constraints that are considered for multiobjective optimization are presented as follows.

2.1. Primary objectives

The generation cost minimization and emission minimization are considered as primary objectives and their quantification is presented as follows.

2.1.1. Generation cost minimization

The objective is to reduce the generation cost (GC) [9] and is expressed as:

$$GC = \sum_{k=1}^{n} a_k + b_k P_k + c_k P_k^2 + |d_k \sin(e_k(P_k^{min} - P_k))|, \tag{1}$$

where a_k, b_k, c_k, d_k, e_k are the cost coefficients of the kth generating station and P_k is the scheduled power of the kth generating station.

2.1.2. Emission minimization

The objective is to reduce the emission of atmospheric pollutants [9], which is expressed as:

$$Emission = \sum_{k=1}^{n} \alpha_k + \beta_k P_k + \gamma_k P_k^2 + \eta_k \ exp(\delta_k P_k), \tag{2}$$

where $\alpha_k, \beta_k, \gamma_k, \eta_k, \delta_k$ are the emission coefficients of the kth generating station.

2.2. Secondary objective

The secondary objective is used to filter the Pareto-optimal set of solutions obtained by simultaneous optimization of both the primary objectives. The new reliability index (AFOR) introduced to address the need of finding the most reliable solution from the Pareto-optimal set based on the FOR of individual generating stations is defined as:

$$AFOR = \frac{\sum_{k=1}^{n} F_k P_k}{\sum_{k=1}^{n} P_k}, \tag{3}$$

where F_k is the forced outage rate of the kth generating station. The qualitative meaning of Eq. (3) is to translate the unavailability of each MW of power scheduled on a particular generating station to a per unit value with respect to total power generated. It is formulated with the assumption that each generating station has one unit. If a generating station has multiple units, the probability of outage should be taken from the capacity outage probability table.

Out of the Pareto-optimal solutions available, the one with the lowest AFOR is chosen as the most reliable solution of the multiobjective optimization.

3. Constraints

The various operational constraints that need to be considered by the system operator are presented as follows.

3.1. Equality constraints

These are the power flow equations that need to be satisfied at each node of the power system network.

$$P_i - jQ_i = |V_i|\angle{-\delta_i} \sum_{k=1}^{N_{Bus}} |Y_{ik}|\,|V_k|\angle\theta_{ik} + \delta_k, \tag{4}$$

where P_i is the real power at bus i, Q_i is the reactive power at bus i, V_i is the voltage at bus i, Y_{ik} is the element corresponding to ith row and kth column in the bus admittance matrix, δ_i is the voltage angle at bus i, θ_{ik} is the angle corresponding to Y_{ik}, and N_{Bus} is the number of buses in the power system network. In Eq. (4), i=1,2,..., N_{Bus}.

3.2. Inequality constraints

The different inequality constraints that need to be bound by the decision variables and other power system parameters are presented as follows.

3.2.1. Generation limits

The minimum and maximum limits of active and reactive power generation are expressed as:

$$P_{Gk}^{min} \le P_{Gk} \le P_{Gk}^{max}, \tag{5}$$

$$Q_{Gk}^{min} \le Q_{Gk} \le Q_{Gk}^{max}, \tag{6}$$

where P_{Gk}^{min} is the minimum active power limit and P_{Gk}^{max} is the maximum active power limit of the kth generating station, and Q_{Gk}^{min} is the minimum reactive power limit and Q_{Gk}^{max} is the maximum reactive power limit of the kth generating station.

3.2.2. Line flow Limits

The maximum limit of MVA flow in a branch is represented as:

$$S_{kl} \leq S_{kl}^{max}, \tag{7}$$

where S_{kl} is the apparent power flowing in the line connecting buses k and l, and S_{kl}^{max} is the maximum limit of apparent power flow in the line connecting buses k and l.

3.2.3. Bus voltage limits

The minimum and maximum limits of bus voltages are expressed as:

$$V_k^{min} \leq V_k \leq V_k^{max}, \tag{8}$$

where V_k^{min}, V_k^{max} are the minimum and maximum voltage limits at bus k, respectively.

The generation rescheduling problem is solved using a modified multiobjective genetic algorithm.

4. Multiobjective generation rescheduling considering AFOR

First, optimization of GC and emission is done considering a single objective at a time, and then the results are compared with those of simultaneous optimization of both objectives. In the case of single-objective optimization, the population is sorted according to feasibility, which results in a higher probability for feasible solutions to participate in crossover. One-point crossover is used and the crossover points are generated by a random number generator to maintain diversity among the chromosomes. Mutation points are generated randomly to ensure that the search for the optimum is not confined to a local area. The process of encoding the real numbers (powers of generator units) in binary form based on required accuracy is adapted from [10]. The genetic algorithm is stopped after the maximum number of generations is reached. An example of crossover and mutation from the GC minimization is illustrated as follows.

Two chromosomes with C_1 and C_2 that are selected for crossover are represented in binary form as:

$$C_1 = (1000\ 0001\ 00001), \tag{9}$$

$$C_2 = (0000\ 1010\ 11000). \tag{10}$$

Selecting the crossover site after the seventh gene, the resulting chromosomes are represented as:

$$C_1{}' = (1000000\ 011000), \tag{11}$$

$$C_2{}' = (0000101\ 100001). \tag{12}$$

Considering the mutations of fifth and seventh genes of $c_1{}'$ and $c_2{}'$, respectively, the resulting chromosomes are represented as:

$$C_1{}'' = (1000\mathbf{1}00\ 011000), \tag{13}$$

$$C_2{}'' = (010010\mathbf{0}\ 100001). \tag{14}$$

In multiobjective optimization, minimization of GC and minimization of emission leads to a set of Pareto-optimal solutions, as simultaneous minimization leads to trade-off with respect to each other. For finding the nondominated set, a modified strength Pareto evolutionary algorithm (SPEA) [11] with a penalty function [12] is used to include the constraints.

The algorithm used for optimization is shown in Figure 1. The decision variables are coded in binary form and the parameters of the genetic algorithm are presented in Table 1. In the step of checking the equality constraints, power flow equations are solved using the Newton–Raphson method and populations with converged solutions have higher probability to participate in crossover. Later inequality constraints are checked and the penalty function is implemented for the population that violates the constraints. The Pareto-optimal solutions within the limits (GC: 22600 $/h, emission: 2000 lb/h) are separated and AFOR is calculated for each solution. The solution with the least AFOR is considered as the final solution of the multiobjective bilevel optimization.

Table 1. Parameters of genetic algorithm.

Population	2000
Number of generations	20
Crossover rate	0.7
Mutation rate	0.1

5. Results and discussion

The proposed method is tested on the IEEE 30-bus system provided in the MATPOWER package [13] with the primary objectives considered one at a time and then compared with multiobjective optimization. The computer programs are coded using GNU/Octave [14] and MATPOWER on a system with a Pentium dual core processor, 4 GB of RAM, and Debian GNU/Linux. The cost and emission coefficients are adapted from [9], while line limits are adapted from [15]. Two cases have been studied to confirm the efficacy of the proposed method. In case-1, the scheduling of the generating stations is found for optimal cost and emission. In case-2, scheduling of generating stations is found considering that the line connecting buses 15 and 23 is out of service because of scheduled maintenance.

The reliability data necessary for calculating AFOR are adapted from [16] and modified as shown in Table 2, where λ is the failure rate and μ is the repair rate of the generating station. The results of both cases are presented as follows.

Table 2. Failure and repair rates of generating stations.

Generator at bus no.	$\lambda(f/year)$	$\mu(r/year)$
1	7.62	87.6
2	9.13	219
5	7.30	175
11	7.1	180
13	7.0	160

5.1. Case-1

The results of only GC minimization are presented in Table 3. Comparing with the emission minimization results shown in Table 4, it is observed that minimizing GC results in cost of 21639 $/h but emission is 2235.7

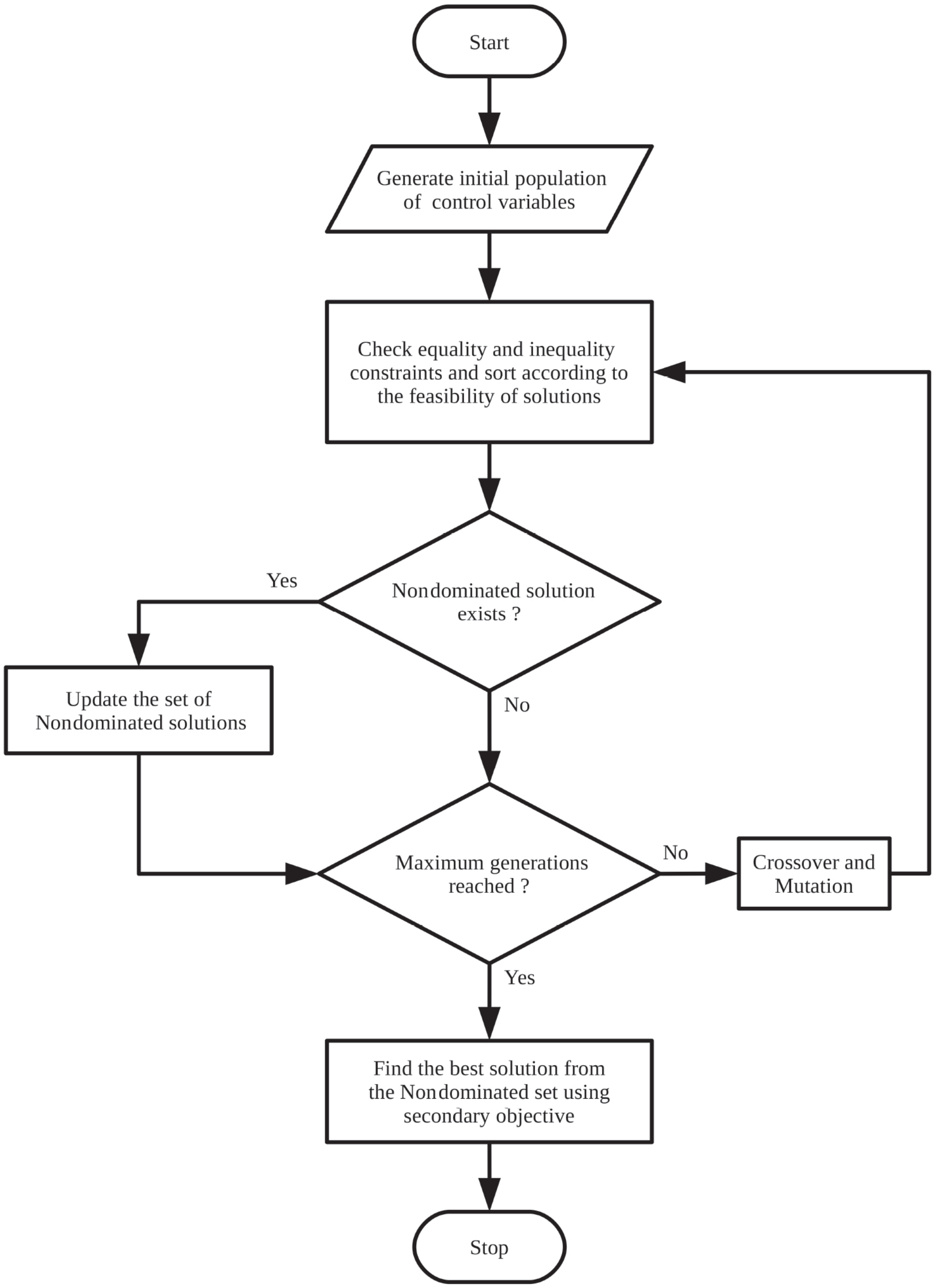

Figure 1. Flow chart of multiobjective generation rescheduling.

lb/h, which is more than the considered limit of 2000 lb/h. Similarly, minimizing emission results in emission of 1649.3 lb/h and cost of 22750 \$/h, which is higher than the considered limit of 22600 \$/h. Thus, the optimization of a single objective without considering the other is leading to a nonoptimal solution.

Owing to the necessity of finding an optimal solution with respect to both the objectives, the nondominated set [8] obtained using the flow chart (Figure 1) is shown in Figure 2. Instead of optimizing all three objectives at a time, reliability is given preference next to financial feasibility and environmental concern. After obtaining the Pareto-optimal front, AFOR is computed for each solution of the Pareto-optimal front and the solution with the least AFOR is taken as the final solution.

Table 3. Results of optimizing generation cost as single objective in case-1.

Scheduled power in MW	Total generation = 291.67 MW
P1 = 176.02	Total demand = 283.40 MW
P2 = 27.721	Total loss = 8.27 MW
P3 = 48.090	Cost = 21639 $/h
P4 = 12.289	Emission = 2235.7 lb/h
P5 = 14.334	AFOR = 0.064176
P6 = 13.224	Time of computation is 20.50 min

Table 4. Results of optimizing emission as single objective in case-1.

Scheduled power in MW	Total generation = 287.66 MW
P1 = 84.940	Total demand = 283.40 MW
P2 = 57.710	Total loss = 4.26 MW
P3 = 45.902	Cost = 22750 $/h
P4 = 33.419	Emission = 1649.3 lb/h
P5 = 26.909	AFOR = 0.051970
P6 = 38.783	Time of computation is 20.73 min

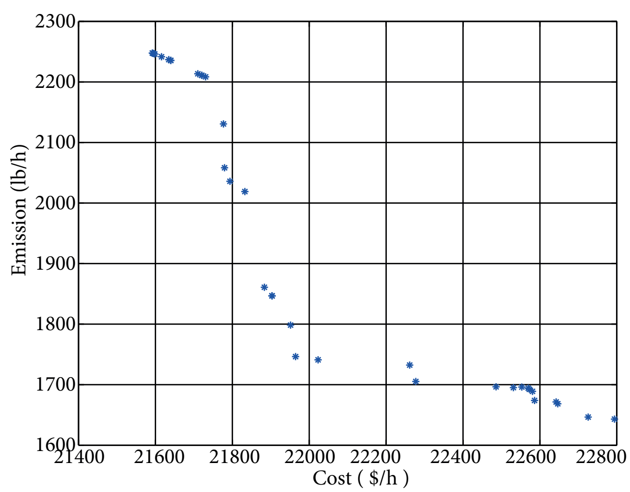

Figure 2. Pareto-optimal front of GC and emission minimization in case-1.

The solutions on the Pareto-optimal front within limits of cost and emission are presented in Table 5 with scheduled powers in MW, cost in $/h, and emission in lb/h. The best solution based on reliability is shown in Table 6. The obtained cost is 22586.02 $/h and the emission is 1673.89 lb/h, which are within the limits of 22600 $/h and 2000 lb/h, respectively.

5.2. Case-2

The branch connecting buses 15 and 23 is considered to be out of service and the solution of generation rescheduling is found by considering the equality and inequality constraints. The results of considering a single

Table 5. Solutions on the Pareto-optimal front within limits in case-1; best results in bold font.

Serial number	P1	P2	P3	P4	P5	P6	Cost	Emission	AFOR
1	100.98	45.23	49.26	32.00	24.34	36.13	22580.65	1688.94	0.05418
2	102.86	45.26	45.26	26.34	28.61	39.83	22572.52	1692.29	0.05442
3	102.85	46.50	48.54	31.63	25.01	33.50	22552.90	1696.08	0.05442
4	127.74	49.97	47.13	11.18	14.73	38.85	21883.33	1860.86	0.05784
5	107.87	50.87	48.68	32.09	10.58	38.42	21964.53	1746.35	0.05523
6	107.32	51.33	48.01	12.46	29.76	39.62	22023.02	1741.02	0.05498
7	126.18	51.99	46.71	34.59	17.55	12.17	21902.99	1846.84	0.05751
8	126.15	51.99	46.71	34.59	17.55	12.20	21903.55	1846.62	0.05750
9	107.87	51.99	46.71	34.59	17.55	29.70	22261.30	1732.34	0.05513
10	118.96	52.16	46.49	34.85	23.35	13.00	21951.45	1798.40	0.05649
11	101.23	52.41	44.75	33.76	23.00	33.03	22531.01	1695.11	0.05420
12	100.37	52.49	48.49	17.66	29.98	39.17	22277.19	1705.22	0.05404
13	**95.10**	**53.22**	**45.26**	**26.34**	**28.61**	**39.47**	**22586.02**	**1673.89**	**0.05334**
14	95.57	57.20	48.49	17.66	29.98	39.17	22485.92	1696.47	0.05338
15	95.87	57.57	47.59	33.14	18.39	35.50	22569.72	1694.17	0.05351

Table 6. Best solution from the Pareto-optimal front based on AFOR in case-1.

Scheduled power in MW	Total generation = 287.99 MW
P1 = 95.10	Total demand = 283.40 MW
P2 = 53.22	Total loss = 4.59 MW
P3 = 45.26	Cost = 22586.02 $/h
P4 = 26.34	Emission = 1673.89 lb/h
P5 = 28.61	AFOR = 0.05334
P6 = 39.47	Time of computation is 30.98 min

objective at a time are presented in Tables 7 and 8. The Pareto-optimal front obtained by considering both objectives at a time is shown in Figure 3. The feasible solutions of the Pareto-optimal front based on the limits of GC and emission are tabulated in Table 9 and the best solution of the Pareto-optimal front based on AFOR is presented in Table 10.

The minimization of GC resulted in a cost of 21643 $/h and an emission of 2236.8 lb/h. This violates the considered emission limit of 2000 lb/h. Similarly, emission minimization resulted in emission of 1649.6 lb/h and cost of 22756 $/h, which exceeds the limit of 22600 $/h. The cost and emission obtained by the proposed algorithm are 22591 $/h and 1674.3 lb/h, respectively, which are within the considered limits.

From the two case studies, it is observed that optimization of GC and emission simultaneously is leading to a Pareto-optimal set of solutions. The best solution from the set is found by using the reliability indices of generating stations. The final solution is considered as the reliable solution of the proposed multiobjective bilevel optimization.

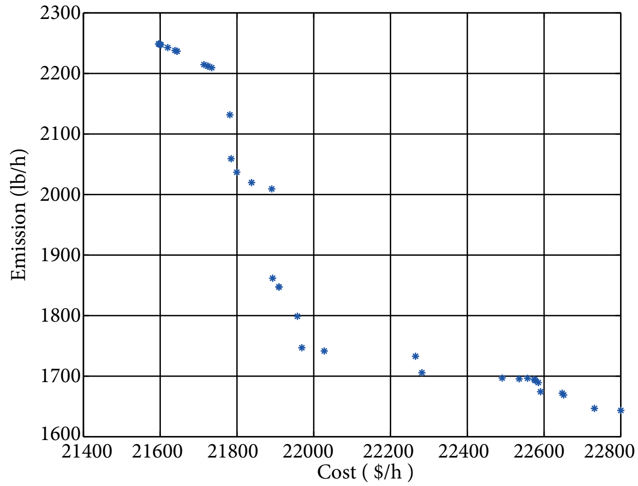

Figure 3. Pareto-optimal front of GC and emission minimization in case-2.

Table 7. Results of optimizing generation cost as single objective in case-2.

Scheduled power in MW	Total generation = 291.80 MW
P1 = 176.15	Total demand = 283.40 MW
P2 = 27.721	Total loss = 8.40 MW
P3 = 48.090	Cost = 21643 $/h
P4 = 12.289	Emission = 2236.8 lb/h
P5 = 14.334	AFOR = 0.064183
P6 = 13.224	Time of computation is 20.66 min

Table 8. Results of optimizing emission as single objective in case-2.

Scheduled Power in MW	Total generation = 287.80 MW
P1 = 85.082	Total demand = 283.4 MW
P2 = 57.710	Total loss = 4.40 MW
P3 = 45.902	Cost = 22756 $/h
P4 = 33.419	Emission = 1649.6 lb/h
P5 = 26.909	AFOR = 0.051983
P6 = 38.783	Time of computation is 20.62 min

6. Conclusion

The paper proposes a novel multiobjective bilevel generation rescheduling algorithm considering the reliability of generating stations. The primary objectives considered are generation cost minimization and emission minimization. As the two primary objectives conflict with each other, a set of Pareto-optimal solutions are obtained by modified SPEA. The best solution from the Pareto-optimal set is found by evaluating AFOR for each solution. The proposed method has been validated on the IEEE 30-bus test system and the results obtained for multiobjective bilevel optimization are globally optimal when compared with the results of single-objective optimization. This method can be used by an ISO for finding the generation schedule for day-ahead scheduling

Table 9. Solutions on the Pareto-optimal front within limits in case-2; best results in bold font.

Serial number	P1	P2	P3	P4	P5	P6	Cost	Emission	AFOR
1	101.13	45.23	49.26	32.00	24.34	36.13	22584.96	1689.39	0.05420
2	103.00	45.26	45.26	26.34	28.61	39.83	22576.91	1692.78	0.05443
3	102.99	46.50	48.54	31.63	25.01	33.50	22556.98	1696.54	0.05443
4	127.91	49.97	47.13	11.18	14.73	38.85	21892.87	1861.75	0.05786
5	108.03	50.87	48.68	32.09	10.58	38.42	21969.03	1746.94	0.05524
6	107.48	51.33	48.01	12.46	29.76	39.62	22027.41	1741.59	0.05499
7	126.28	51.99	46.71	34.59	17.55	12.17	21909.05	1847.38	0.05751
8	126.26	51.99	46.71	34.59	17.55	12.20	21909.62	1847.16	0.05751
9	108.01	51.99	46.71	34.59	17.55	29.70	22265.18	1732.85	0.05514
10	119.06	52.16	46.49	34.85	23.35	13.00	21957.43	1798.87	0.05650
11	101.37	52.41	44.75	33.76	23.00	33.03	22535.20	1695.55	0.05421
12	100.52	52.49	48.49	17.66	29.98	39.17	22281.80	1705.70	0.05405
13	**95.25**	**53.22**	**45.26**	**26.34**	**28.61**	**39.47**	**22590.90**	**1674.30**	**0.05336**
14	95.72	57.20	48.49	17.66	29.98	39.17	22490.86	1696.89	0.05339
15	96.02	57.57	47.59	33.14	18.39	35.50	22574.50	1694.59	0.05352

Table 10. Best solution from the Pareto-optimal front based on AFOR in case-2.

Scheduled power in MW P1 = 95.25	Total generation = 288.14 MW Total demand = 283.40 MW
P2 = 53.22	Total loss = 4.74 MW
P3 = 45.26	Cost = 22591 $/h
P4 = 26.34	Emission = 1674.3 lb/h
P5 = 28.61	AFOR = 0.053358
P6 = 39.47	Time of computation is 32.28 min

and preventive maintenance. The time of computation can be reduced by considering a smaller population, but it may lead to a local optimum. The proposed algorithm can be used for transmission congestion management by reducing the time of computation when the decision needs to be made in less time.

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