Transmission Line Management Using Multi-objective Evolutionary Algorithm

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Abstract. This paper presents an effective method of transmission line management in power systems. Two conflicting objectives 1) generation cost and 2) transmission line overload are optimized to provide non-dominated Pareto-optimal solutions. A fuzzy ranking-based multi-objective differential evolution (MODE) is used to solve this complex nonlinear optimization problem. The generator real power and generator bus voltage magnitude is taken as control variables to minimize the conflicting objectives. The fuzzy ranking method is employed to extract the best compromise solution out of the available non-dominated solutions depending upon its highest rank. N-1 contingency analysis is carried out to identify the most severe lines and those lines are selected for outage. The effectiveness of the proposed method has been analyzed on standard IEEE 30 bus system with smooth cost functions and their results are compared with non-dominated sorting genetic algorithm-II (NSGA-II) and Differential evolution (DE). The results demonstrate the superiority of the MODE as a promising multi-objective evolutionary algorithm to solve the power system multi-objective optimization problem.

1 Introduction

Optimal power flow (OPF) is an important tool for power system management. The aim of OPF problem is to optimize one or more objectives by adjusting the power system control variables while satisfying a set of physical and operating constraints such as generation and load balance, bus voltage limits, power flow equations, and active and reactive power limits. A variety of optimization techniques had been applied to solve the OPF problem such as gradient method [1], linear programming method [2] and interior point method. In conventional optimization methods, identification of global minimum is not possible. To overcome the difficulty, evolutionary algorithms like genetic Algorithm (GA) [3], particle swarm optimization [4], differential evolution [5], gravitational search algorithm [6], tabu search algorithm [7] and artificial bee colony algorithm [8] had been proposed.

In [9], the authors' proposed a fuzzy logic based approach to alleviate the network overloads by generation rescheduling. The generation shift sensitivity factor (GSSF)

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was used to decide the changes in generation. In [10], the authors' proposed an optimal location of interline power flow controller (IPFC) in a power system network using artificial bee colony algorithm (ABC). Minimization of line loss, economic dispatch of generators, improve power flow and reduction in the overall system cost which includes the cost of active power generation and the installation cost of IPFC were also considered for obtaining the optimal location. In [11], the authors' proposed a static security enhancement through optimal utilization of thyristor-controlled series capacitors (TCSC). The branches ranking in the system was based on determination of single contingency sensitivity (SCS) index which helped to decide the best locations for the TCSCs. The objective of the optimization problem was to eliminate or minimize line overloads as well as the unwanted loop flows under single contingencies. In [12], the authors' proposed the use of genetic algorithm (GA) and multi-objective genetic algorithm (MOGA) to alleviate the violations of the overloaded lines and minimize the transmission power losses for different operating conditions. In [13], the authors' proposed a multi-objective particle swarm optimization (MOPSO) method for transmission line overload management. Two competing objectives were considered for minimization such as line overloads and operating cost of generators. The overloads in a transmission network were alleviated by generation rescheduling. In [14], the authors' proposed a graphical user interface (GUI) based on a genetic algorithm. It was used to determine the optimal location and sizing parameters of multi type FACTS devices which facilitate maximization of power system loadability in a transmission network. In [15], the authors' proposed a non-dominated sorting genetic algorithm (NSGA), niched multi-objective genetic algorithm (NPGA) and strength multi-objective evolutionary algorithm (SPEA) to minimize two competing objective functions such as fuel cost and emission. The results of these proposed methods were compared to each other. The SPEA method had better diversity characteristics and was more efficient when compared to other methods. In [16], the authors' proposed an application of hybrid differential evolution with particle swarm optimization (DEPSO) to solve the maximum loadability problem. The results were compared with multi agent hybrid particle swarm optimization (MAHPSO) and differential evolution (DE). This proposed algorithm had improved the loadability margin with less number of iterations by consuming more time per iteration when compared to other algorithms. In [17], the authors' proposed a survey on development of multi-objective evolutionary algorithms (MOEAs). It covered algorithmic frameworks such as decomposition-based MOEAs (MOEA/Ds), memetic MOEAs, co-evolutionary MOEAs, selection and offspring reproduction operators, MOEAs with specific search methods, MOEAs for multimodal problems, constraint handling and MOEAs, computationally expensive multi-objective optimization problems (MOPs), dynamic MOPs, noisy MOPs, combinatorial and discrete MOPs, benchmark problems, performance indicators and applications.

In this paper, a fuzzy ranking based multi-objective differential evolution for overload management in power system network is presented with an illustrated example.

The organization of the paper is as follows: Section 2 presents the optimization problem formulation for transmission line overload management. Section 3 presents the algorithm of proposed MODE for transmission line overload management. The simulation results for different contingency cases in IEEE 30 bus system is presented in section 4. Finally, conclusion and future works is given in Section 5.

2 Problem Formulation

The objective function of the proposed method is to find an optimum value of shift in active power generation and generator bus voltage magnitude along with network constraints so as to minimize the total generation cost and line overloads simultaneously in the network. The problem of proposed MODE may be stated as follows.

2.1 Objective Function

Objective 1. Minimize total generation cost

$$\text{Generation cost, } GC = \sum_{i=1}^{NG} \left(a_i P_{gi}^{\ 2} + b_i P_{gi} + C_i \right) \tag{1}$$

where:

GC Generation cost

N_G Number of participating generators

P_{gi} Generation of i^{th} generator

a_i, b_i, c_i Cost coefficients of generator i

Objective 2. Minimize transmission line overload by reducing Overload Index

$$\text{Overload Index, } OI = \sum_{i=1}^{N_L} \left(LF_i - L_{capi_i} \right)^2 \tag{2}$$

where:

OI Overload Index

N_L Number of overloaded lines

LF_i MVA flow on line i

L_{capi_i} MVA capacity of line i

2.2 Constraints

2.2.1 Equality Constraints

Generation/load balance Equation

$$\sum_{i=1}^{N_G} P_{gi} - \sum_{i=1}^{N_D} P_{Di} - P_L = 0 \tag{3}$$

2.2.2 Inequality Constraints

(i) Voltage constraints

$$V_{i,\min} \le V_i \le V_{i,\max} \tag{4}$$

(ii) Generator constraints

$$P_{gi,\min} \le P_{gi} \le P_{gi,\max} \tag{5}$$

$$V_{gi,\min} \leq V_{gi} \leq V_{gi,\max} \tag{6}$$

3 Proposed MODE Algorithm

MODE was proposed by Xue et al. in [18]. This algorithm uses a variant of the original DE, in which the best individual is adopted to create the offspring. A multi-objective-based approach is introduced to implement the selection of the best individuals.

The main algorithm consists of initialization of population, fitness evaluation, Pareto-dominance selection, performing DE operations and reiterating the search on population to reach true Pareto-optimal solutions.

The steps involved in the proposed MODE for transmission line overload management are described below.

Step 1: Set up MODE parameters like population size, number of generations, crossover probability and scaling factor.
Step 2: Read line data, bus data and cost for each generator.
Selection of control variables embedded in the individuals is a first step while applying evolutionary computation algorithm. Generator real powers redispatch and generator bus voltage magnitude is the control variables in this work. Hence, the control variables are generated randomly satisfying their practical operation constraints (5) and (6).
Step 3: For each member of population, run newton raphson (NR) power flow and compute slack bus power and check for limit violations if any. If it violates the operational limit then the corresponding member is regenerated. For each member of population, run NR power flow to evaluate objective functions 1 and 2 using equations (1) and (2). Identify the individuals that give non-dominated solutions in the current population and store them in non-dominated elitist archive (NEA). Set generation counter, G=0.
Step 4: Perform mutation and crossover operations using equations (7) and (8) on all the members of the population, i.e., for each parent P_i

$$V_i^{(G)} = X_{r1}^{(G)} + F(X_{r2}^{(G)} - X_{r3}^{(G)}), i = 1,...,N_p \tag{7}$$

$$U_i^{(G)} = U_{j,i}^{(G)} = \begin{cases} V_{j,i}^{(G)} & if\ rand_j(0,1) \leq CR \\ x_{j,i}^{(G)} & otherwise \end{cases} \tag{8}$$

Step 5: Evaluate each member of the population. Check the dominance with its parents. If the candidate dominates the parent, the candidate replaces the parent. If the parent dominates the candidate, the candidate is discarded. Otherwise, the candidate is added to a temporary population (tempPop).
Step 6: Add the latest solution vectors (current population) to the tempPop. Then use the non-dominated sorting and crowding assignment operators to select the individuals to the next generation.

Step 7: Store the non-dominated solutions in the NEA. If NEA size exceeds the desired number of Pareto-optimal set, then select desired number of the least crowded members with the help of crowding assignment operator. Empty the tempPop.
Step 8: Increment the generation counter, G to G+1 and check for termination criteria. If the termination criterion is not satisfied, then go to Step 4; otherwise output the non-dominated solution set from NEA.
Step 9: Apply fuzzy ranking method, determine membership values of the objective functions 1 and 2 using equation (9).

$$\mu(F_i)=\begin{cases}1; \quad Fi \le F_i^{\min} \\ \dfrac{F_i^{\max}-Fi}{F_i^{\max}-F_i^{\min}}; F_i^{\min} \le F_i \le F_i^{\max} \\ 0; Fi \ge F_i^{\max}\end{cases} \tag{9}$$

where:

$F_i^{\min}$ and $F_i^{\max}$ are the expected minimum and maximum values of i^{th} objective function.

The value of the membership function indicates how much (in scale from 0 to 1) a solution is satisfying the i^{th} objective F_i. The best solution can then be selected using fuzzy min-max proposition.
Step 10: Determine the best compromise solution of the objective functions 1 and 2 using equation (10).

$$\mu_{bestsolution} = Max\left\{\min\left[\mu(F_j)\right]^k\right\} \tag{10}$$

where:

j is number of objectives to be minimized and k are number of Pareto-optimal solutions obtained.

4 Simulation Results

The simulation studies are performed on system having 2.27 GHz Intel 5 processor with 2 GB of RAM in MATLAB environment. The proposed MODE is applied to minimize two conflicting objectives of generation cost and line overload for different contingency cases in IEEE 30 bus system. The transmission line limits and generator cost coefficients are taken from [19]. The upper and lower voltage limits at all the buses except slack are taken as 1.10 p.u and 0.95 p.u respectively. The slack bus voltage is fixed to its specified value of 1.06 p.u. To demonstrate the effectiveness of the proposed method, three different harmful contingency cases are considered which are shown in table 1. The results of all three cases are compared with other evolutionary algorithms. For the studies, the following parameters are used.
Population size: 40
No. of generation: 100
Scaling factor: 0.3
Crossover probability: 0.6.

Table 1. Simulated Cases

Test system	Simulated cases	
IEEE 30 Bus	A	Outage of line 1-2 under base case
	B	Outage of line 1-3 under base case
	C	Outage of line 2-5 under 20% increased load case

The Summary of contingency analysis for the test system before generation rescheduling is summarized in table 2. The control variable setting of the proposed method to minimize the generation cost and line overload for all three cases is shown in table 3. The control variable setting of NSGA-II method to minimize the generation cost and line overload for all three cases is shown in table 4. The control variable setting of the single objective DE method to minimize the line overload for all three cases is shown in table 5. The four intermediate solutions with their membership value out of the obtained non-dominated solution set using the proposed method for all three cases are shown in table 6. The best solutions are shown in bold in table 6 and have a rank of 0.6621, 0.6560 and 0.7813 which means that the two conflicting objectives are satisfied at least 66.21%, 65.60% and 78.13%. The Pareto-optimal solution for the proposed method compared with NSGA-II method for all three cases are shown in table 7.

Table 2. Summary of contingency analysis for IEEE 30 bus system

Cases	Outage line	Line overloaded	Line limit (MVA)	Actual power flow (MVA)	Overload factor (OLF)	OI	Total power violation (MVA)
A	1-2	1-3	130	307.0136	2.3616	61245	426.7022
		3-4	130	279.6035	2.1508		
		4-6	90	175.5527	1.9506		
		6-8	32	46.5144	1.4536		
B	1-3	1-2	130	274.0264	2.1079	21969	196.1237
		2-4	65	86.1203	1.3249		
		2-6	65	92.7203	1.4265		
		6-8	32	35.2567	1.1018		
C	2-5	1-2	130	213.9041	1.6454	21190	359.8447
		1-3	130	140.0342	1.0772		
		2-4	65	91.2433	1.4037		
		3-4	130	130.0068	1.0001		
		2-6	65	126.3806	1.9443		
		4-6	90	152.5479	1.6950		
		5-7	70	136.8100	1.9544		
		6-7	130	157.6918	1.2130		
		6-8	32	53.2260	1.6633		

Table 3. Control variable setting of the proposed method for all three cases

Control variables	Variable setting								
	Solution I (Best generation cost)			Solution II (Best overload index)			Solution III (Best compromise solution)		
	A	B	C	A	B	C	A	B	C
P_1	144.90	149.42	202.02	129.67	129.63	167.59	138.16	141.38	191.36
P_2	57.78	54.08	52.44	64.64	60.65	42.10	63.35	57.16	47.24
P_5	24.48	22.31	30.28	25.42	24.63	48.33	23.16	22.79	39.92
P_8	33.24	33.02	34.44	34.57	32.20	33.89	33.77	32.69	34.18
P_{11}	21.66	16.06	22.18	20.00	24.21	27.85	20.89	22.06	24.45
P_{13}	16.46	19.27	20.34	21.82	21.19	35.73	18.20	17.33	21.47
V_1	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060
V_2	1.044	1.035	1.054	1.020	1.034	1.028	1.026	1.034	1.047
V_5	1.028	0.993	0.961	0.992	0.991	0.953	1.011	1.001	0.950
V_8	1.030	0.996	1.029	1.020	1.019	1.015	1.027	1.001	1.026
V_{11}	1.094	1.062	1.078	1.092	1.069	1.084	1.098	1.070	1.091
V_{13}	1.076	1.040	1.078	1.054	1.056	1.045	1.045	1.041	1.100

Table 4. Control variable setting of NSGA-II method for all three cases

Control variables	Variable setting								
	Solution I			Solution II			Solution III		
	A	B	C	A	B	C	A	B	C
P_1	145.35	149.50	204.24	129.95	129.99	165.75	138.55	141.17	185.49
P_2	68.01	51.23	55.02	68.26	61.60	44.95	68.22	56.78	47.36
P_5	24.85	23.32	29.21	27.57	26.28	49.77	25.96	24.15	39.64
P_8	31.28	29.81	32.27	34.98	30.77	34.42	33.59	30.24	34.46
P_{11}	14.37	23.41	23.33	14.66	26.75	21.47	14.26	24.32	21.78
P_{13}	14.61	16.73	18.08	20.61	17.04	39.94	16.77	16.78	29.45
V_1	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060
V_2	1.023	1.034	1.060	1.018	1.038	1.013	1.018	1.034	1.045
V_5	0.997	1.023	0.969	0.993	1.025	0.952	0.994	1.022	0.985
V_8	1.019	1.018	1.038	1.015	1.015	0.979	1.018	1.020	1.032
V_{11}	1.079	1.070	1.095	1.071	1.090	1.079	1.085	1.070	1.100
V_{13}	1.100	1.022	1.100	1.088	1.055	1.100	1.099	1.023	1.073

Table 5. Control variable setting of single objective DE method for all three cases

Control variables	Variable setting			Control variables	Variable setting		
	A	B	C		A	B	C
P_1	126.70	128.15	184.22	V_1	1.060	1.060	1.060
P_2	70.89	69.61	24.81	V_2	1.024	1.033	1.035
P_5	26.55	25.02	48.27	V_5	0.999	0.988	0.955
P_8	31.97	32.71	32.17	V_8	0.980	0.976	1.001
P_{11}	16.36	10.00	29.05	V_{11}	0.982	1.021	1.024
P_{13}	24.43	28.09	37.47	V_{13}	0.961	0.950	1.078

Table 6. Pareto-optimal intermediate solutions of the proposed method based on fuzzy ranking

Cases	Generation Cost ($/h)	OI	μ_1	μ_2	μ_{min}
A	843.80	1.99	0.0837	0.9902	0.0837
	841.42	**66.71**	0.6621	0.6695	**0.6621**
	843.50	4.17	0.1561	0.9793	0.1561
	841.88	40.17	0.5500	0.8009	0.5500
B	822.65	151.42	0.7480	0.5986	0.5986
	823.66	114.17	0.6546	0.6974	0.6546
	823.21	**129.79**	0.6958	0.6560	**0.6560**
	829.39	2.18	0.1244	0.9942	0.1244
C	1058.41	305.76	0.9592	0.3951	0.3951
	1069.89	73.19	0.7023	0.8552	0.7023
	1066.36	**106.34**	0.7813	0.7896	**0.7813**
	1072.04	62.93	0.6543	0.8755	0.6543

Table 7. Pareto-optimal solution for all three cases

Pareto-optimal solution	Method	Cases	Generation cost ($/h)	OI
Solution I	Proposed	A	840.16	282.89
	NSGA-II		840.63	284.80
	Proposed	B	819.92	377.26
	NSGA-II		821.10	380.08
	Proposed	C	1056.59	505.46
	NSGA-II		1056.24	617.18
Solution II	Proposed	A	844.15	0
	NSGA-II		844.97	0
	Proposed	B	830.74	0
	NSGA-II		831.44	0
	Proposed	C	1101.27	0
	NSGA-II		1110.51	0
Solution III	Proposed	A	841.42	66.71
	NSGA-II		841.73	73.64
	Proposed	B	823.21	129.79
	NSGA-II		824.48	125.49
	Proposed	C	1066.36	106.34
	NSGA-II		1069.09	125.68

From table 7, it is clear that; overload is managed by changing both rescheduling of generators active power and generator bus voltage magnitude for all three cases. If the operator wants to alleviate the line overload completely, he will choose solution II. However, if the operator allows some overload and takes solution I. To satisfy solutions I and II, the operator will choose solution III which gives best compromise solution. In line 1-2 outage under base load case, GA based approach reported in [20] was not completely minimize the severity index even if rescheduling of generators active power and generator bus voltage magnitude and still has the severity index of 2.473 when compared to proposed method. The control variable setting of GA based approach to minimize the line overload is shown in table 8. The generation cost and real power loss for best overload index of the proposed method compared with NSGA-II and single objective DE for all three cases are shown in table 9.

Table 8. Control variable setting of GA based approach for case A

Control variables	Generator active power (MW)	Control variables	Generator bus voltage (p.u)
P_1	145.49	V_1	1.035
P_2	57.36	V_2	0.998
P_5	24.42	V_5	0.959
P_8	34.82	V_8	0.967
P_{11}	18.03	V_{11}	1.02
P_{13}	17.2	V_{13}	0.9500

Table 9. The generation cost and real power loss for best overload index

Method	Cases					
	Generation Cost ($/h)			Real Power Loss (MW)		
	A	B	C	A	B	C
Proposed	844.15	830.74	1101.27	12.73	9.12	15.41
NSGA-II	844.97	831.44	1110.51	12.62	9.04	16.22
DE	852.62	840.41	1112.72	13.50	10.19	15.91

The Pareto-optimal front of generation cost and overload index for all three cases compared with NSGA-II method are shown in figure 1, 2 and 3 respectively.

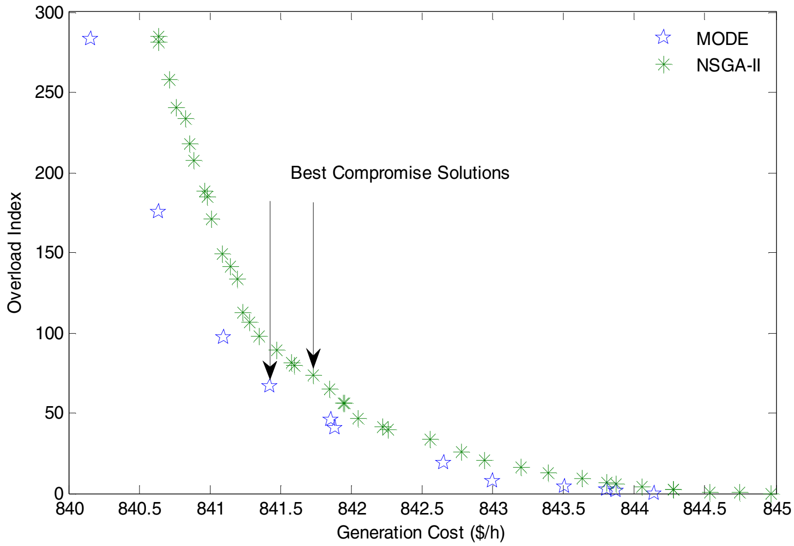

Fig. 1. Pareto-optimal front for Case A

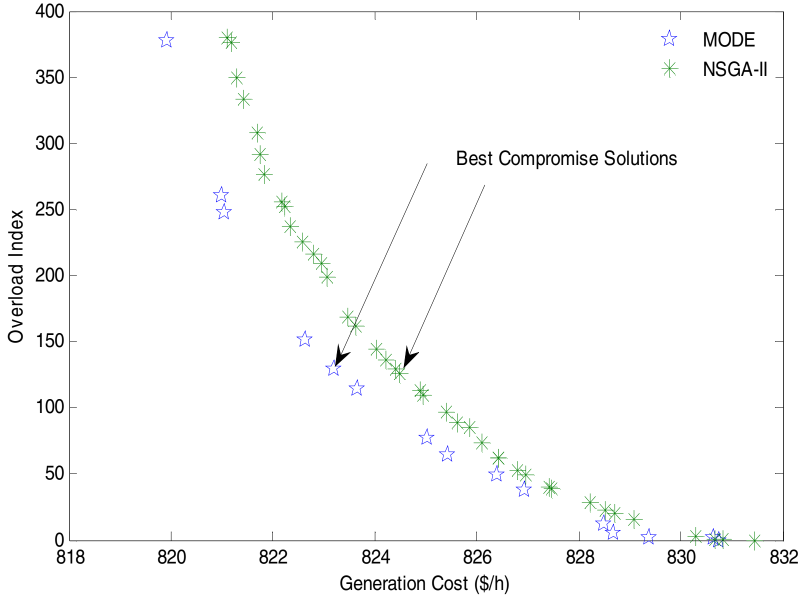

Fig. 2. Pareto-optimal front for Case B

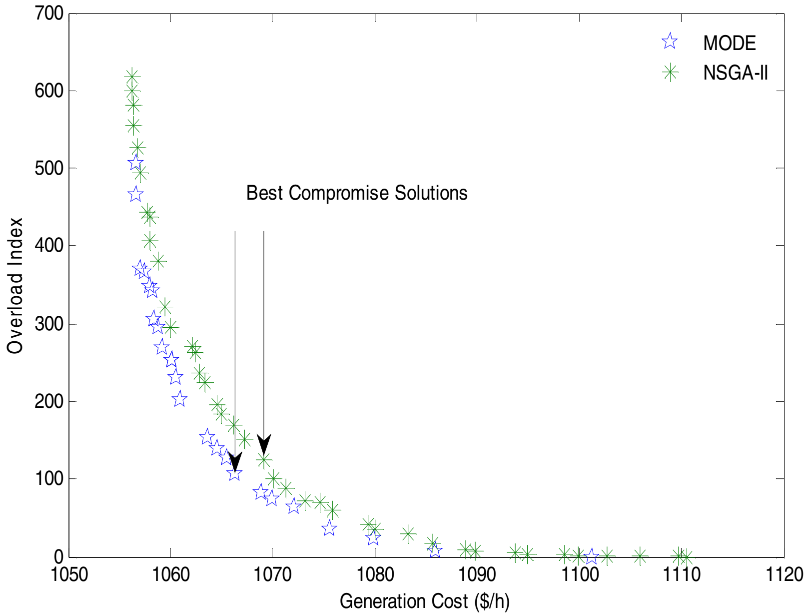

Fig. 3. Pareto-optimal front for Case C

In all three cases, the proposed method relieves all the overloaded lines reported in table 2 by changing both rescheduling of generators active power and generator bus voltage magnitude. From table 9, it is clear that; the proposed method relieves all the overloaded lines with a minimum generation cost when compared to other methods. The computation time for proposed and NSGA-II methods for Case A , Case B and Case C are 22.94, 22.87 and 23.99 and 33.59, 31.30 and 33.98 seconds respectively for 100 generations.

5 Conclusion and Future works

This paper has proposed multi-objective differential evolution based transmission line overload management by both rescheduling of generators active power and generator bus voltage magnitude in a contingent power network. The proposed method has been tested and examined on the standard IEEE-30 bus system. Line overloads are simulated due to unexpected line outage under base case and 20% increased load conditions. In all the considered three cases A, B and C, the proposed method has relieved all the overloaded lines with a minimum generation cost of 844.15 $/h, 830.74 $/h and 1101.27 $/h respectively, when compared to NSGA-II and DE methods. The proposed MODE is capable of handling two conflicting objectives and provides for a set of non-dominated Pareto-optimal solutions with least computation time when compared to NSGA-II. This helps the system operator to select the proper solution for overload alleviation and generation cost minimization whereas, single objective DE algorithm does not provide any choice for the operator and gives only one best solution considering the objectives.

For future works, we aim to extend the proposed approach with Euclidean minimum spanning tree-based multi-objective optimization evolutionary algorithm for overload management in large power system network with inclusion of series FACTS devices along with generation rescheduling and validation using T-test.

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