An Environment Friendly Energy-Saving Dispatch Using Mixed Integer Linear Programming Relaxation in the Smart Grid with Renewable Energy Sources

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Abstract

Electrical energy demand has risen over the world which results in development of smart grid. Smart grid has identified the areas that requires improvement. Because of the focus on cost-effective operation as well as environmental concerns in the electrical power system, the complexity of the optimization function has increased. In this study, a new energy-saving

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dispatch model is developed, which takes into account renewable energy sources in the smart grid as well as dynamic generation-load interaction. Moreover, the active demand response idea is employed for interruptible loads during peak demand. During off-peak load periods and compensating loads, the proposed energy-saving dispatch system operates on a bi-level dispatch system. Lower level dispatch works with four dispatch functions such as interruptible load cost, compensation load cost, renewable energy source cost, and emission saving cost. Whereas, upper level dispatch deals with cost functions for operation and emission. Renewable energy sources are represented as a generating unit as well as a load based on usage in this work. Linear programming relaxation and mixed integer linear programming relaxation methodologies are used to solve the constrained optimization problem. The outcomes of the experiments were compared with existing methodologies such as the classic NSGA-II and the improved NSGA-II. Furthermore, the algorithm's time complexity was examined. The proposed solution has been implemented using the IEEE-30 bus standard. The performance results demonstrate considerable reductions in operating costs as well as reductions in emissions.

Keywords: Energy storage, renewable energy source, optimization, pareto optimization, integer linear programming.

1 Introduction

In the age of deregulation, the power plant business is undergoing a revolutionary transformation. Applying creative concepts for the benefit of society, because the electrical power business is so important to the development of society and economy [1–3]. The power industry, on the other hand, relies heavily on fossil fuels to generate electricity [4]. As a result, carbon emissions from these power facilities are a source of concern. Countries with dense populations, such as India and China, are now enacting measures to decrease carbon emissions. India's government plans to reduce carbon emissions by 35% by 2030 [5]. Solar PV and wind based generation systems are being employed with improved inverters and control algorithms for reducing the carbon emission [6–9]. Carbon emissions are caused not only by power generation, but also by consumption patterns [10]. Big buildings contribute to carbon emissions from the consumer's perspective [11, 12]. Combustion of fossil fuels for heating, cooling, and lighting, as well as powering appliances and electrical equipment, is a major source of pollutants.

A carbon emission-reduction dispatch, in conjunction with generator and consumer concerns, can successfully promote energy saving for the benefits of society. In the current climate of high energy consumption, smart grids are playing a more active role in the development of policies and regulations for the deployment of new technologies [13–18]. Demand response, reliability, renewable resources, electric storage, and electric transportation are all trends that the Department of Energy (DoE) has identified [19].

Many people from all around the world have contributed to a literature review on carbon emission reduction or energy-saving dispatch. It is a prospective trend to include flexible loads in energy saving dispatch models such as air conditioners, electric water heaters, electric vehicles, power system stabilizers, and so on [20–22]. In DoE, a screenshot of a transition to a smart grid was shown in a panoptic view grid-wise [23, 24] and modern grid strategy [25].

This paper presents a model with generation, carbon emission mathematical formulation with demand response with constraints on generation, emission limits and on-off time for equipment connected with the network. In order to ensure life span of equipment, user comfortableness several constrains taken in to consideration. Solution steps of the proposed model involve Linear Programming Relaxation (LPR) and Mixed Integer Linear Programming Relaxation (MILPR) methods. The proposed methodology has been illustrated with IEEE 30 standard bus data. Experimental results are compared with existing methods such as traditional NSGA-II and improved NSGA-II. Time complexity of methodologies has been analyzed. Experimental result shows significant improvement in result with reduced time complexity.

Paper is organized as follows: Section 2 is problem formulation and Section 3 presents solution procedure. In Section 4, time complexity analysis of presented algorithm presented. Section 5 is for performance evaluation with experimental results. Section 6 is conclusion of the work.

2 Problem Formulation

In this section, the formulation of carbon emission reduction dispatch problem has been done. The algorithm not only minimizes the cost of generation with emission reduction (generation and load side) but also ensures the user's satisfaction with minimum break time that helps in ensuring large life span of equipment in power system network.

$$C = Min\left\{\begin{aligned} &\sum_{t=1}^{T}\Bigg[\sum_{k=1}^{N_G}(p_k P_{k,t}^2 + q_k P_{k,t} + r_k)\pi_k \\ &\quad + \sum_{k=1}^{N_G}(u_k P_{k,t}^2 + v_k P_{k,t} + w_k)\tau \\ &\quad + \sum_{d=1}^{D}\sigma_d X_{Id,t} P_{Id,t} + \sum_{m=1}^{M}\xi_m X_{Hm,tt} P_{Hm,t} \\ &\quad + \sum_{n=1}^{N}\varphi(P_{nd,t})\tau + \frac{1}{D}\sum_{d=1}^{D} BT_{d,t} \\ &\quad - \sum_{t=1}^{T}\sum_{re=1}^{RE}(F_{Capital} - C_{G,RE} * P_{G,RE})\Bigg] \end{aligned}\right. \tag{1}$$

Subject to,

$$\sum_{k=1}^{N_G} P_{i,t} - \sum_{n=1}^{N} P_{nd,t} - \sum_{l=1}^{L} P_{loss} = 0 \tag{2}$$

$$\begin{cases} P_{rin,t} = P_{r,t} - P_{nr,t} \\ Q_{rin,t} = Q_{r,t} - Q_{nr,t} \\ V_r^{\min} \le V_{r,t} \le V_r^{\max} \\ S_{l,t} \le S_l^{\max} \end{cases} \tag{3}$$

Where, $\mathrm{p_k}$, $\mathrm{q_k}$ and $\mathrm{r_k}$ are cost function parameters and $\mathrm{u_k}$, $\mathrm{v_k}$ and $\mathrm{w_k}$ are emission function parameters. σ_d is compensation cost for user d as interruptible load, $X_{Id,t}$ is use state vector for interruptible load at tie t,ξ_m is incentive load cost for user m with $X_{Hm,t}$ as state vector for incentive load at time t, $\varphi(P_{nd,t})$ is carbon emission function for load $P_{nd,t}$ at time t, $BT_{d,t}$ is break time for load d at time t, and last part shows net cost saved from renewable energy source later given in Equation (8). Equation (1) presents mathematical expression to optimize the cost of operation, emission of thermal units, payoff interruptible loads, incentive loads, and cost of renewable energy along with power balance constraints in Equation (2) and upper and lower bound limits in Equation (3). Also, $S_{l,t}$ represents complex ac power at time of line l (MVA) and $S_l^{\max}$ shows upper bound of complex ac power of line l (MVA).

$$\begin{cases} P_k^{\min} \le P_{k,t} \le P_k^{\max} \\ Q_k^{\min} \le Q_{k,t} \le Q_k^{\max} \\ P_{k,t} - P_{k,t-1} \le \Delta P_{k,up} \\ P_{k,t-1} - P_{k,t} \le \Delta P_{k,down} \end{cases} \tag{4}$$

Where, P_k^{min}, P_k^{max} and Q_k^{min}, Q_k^{max} are minimum and maximum active and reactive power flow limits, respectively. $\Delta P_{k,up}$ is maximum limit of increasing power generation rate for kth unit of thermal based generation (MW/h) and $\Delta P_{k,down}$ shows maximum limit of decreasing power generation rate for kth unit of thermal based generation (MW/h). Equation (4) is showing upper and lower bounds of power flow such as active power, reactive power and ramp up rates.

$$\begin{cases} P_{Id,t} \in \ [P_{Id}^{\min}, P_{Id}^{\max}] \\ P_{Hm,t} \in \ [P_{Hm}^{\min}, P_{Hk}^{\max}] \\ P_{nd,t} \in \ [P_{nd}^{\min}, P_{nd}^{\max}] \\ Min\left(\displaystyle\sum_{d=1}^{D} \sigma_d X_{Id,t} P_{Id,t} + \sum_{m=1}^{M} \xi_m X_{Hm,tt} P_{Hm,t}\right) \\ \qquad \le Min\left(\displaystyle\sum_{k=1}^{N_G} (u_k P_{k,t}^2 + v_k P_{k,t} + w_k)\tau + \sum_{n=1}^{N} \varphi(P_{nd,t})\tau\right) \end{cases} \tag{5}$$

Where, $P_{Id,t}$, $P_{Hm,t}$ and $P_{nd,t}$ are payoff interruptible loads, incentive loads, for load emission are represented by the third, fourth, and fifth parts of Equation (1), respectively. Equation (5) presents upper and lower bounds of active power of same loads such as interruptible loads, incentive loads, and load emission. Figure 1 shows the system model of the network in which renewable energy source is connected with energy storage system to improve system reliability in absence of renewable resources.

When renewable source is available, Equation (6) shows that when energy from renewable source available then it will supply power to grid, energy storage system and load of consumer. While in condition of non-availability

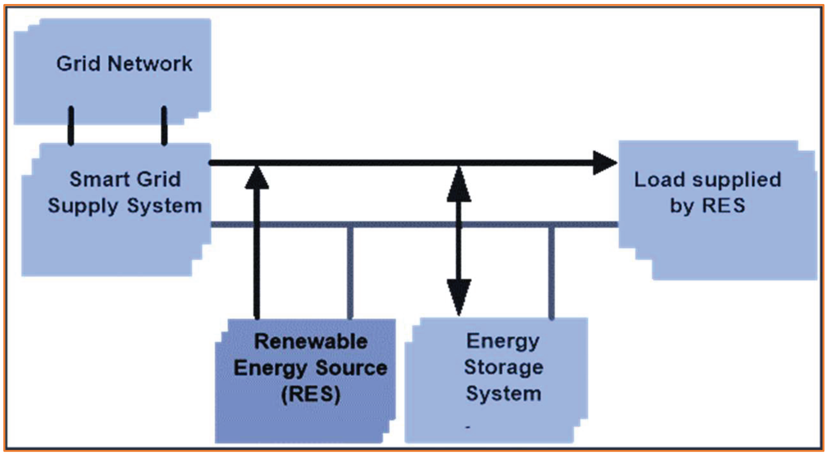

Figure 1 System model with renewable energy sources.

of renewable source (i.e. $P_{RES} = 0$) Equation (7) is used.

$$P_{RES} = P_{Grid} + P_{ESS} + P_L \quad P_{\text{Grid}} \leq 0, P_{ESS} \leq 0, P_L > 0 \tag{6}$$

$$P_{Grid} + P_{ESS} = P_L \quad P_{\text{Grid}} \geq 0, P_L > 0, P_{ESS} \in R \tag{7}$$

Cost function is given as:

$$F_{RES} = F_{Capital} - F_{recovered}(P_{Grid} < 0) \tag{8}$$

With consideration of maintenance and operational cost is zero.

$$F_6 = \sum_{t=1}^{T} \sum_{re=1}^{RE} (F_{Capital} - C_{G,RE} * P_{G,RE}) \tag{9}$$

$$\sum_{d=1}^{D} P_{nd,t} = P_{D,t} - \sum_{d=1}^{D} X_{Id,t} * P_{Id,t} + \sum_{m=1}^{M} X_{Hm,t} * P_{Hm,t} \tag{10}$$

$$HLS_{j,t} = P_{D,t} - \sum_{k=1}^{K} U_{Ig,k} * P_{Ig,t} + \sum_{m=1}^{M} U_{IH,m} * P_{Ih,t} - \sum_{re=1}^{RES} P_{G,re} \tag{11}$$

$$\phi(P_{nd,t}) = \mu_d P_{nd,t} + \omega_d \tag{12}$$

Equation (6) presents expression for load on renewable source, in condition when renewable resource is available and energy storage system is storing power (so acting as load). Equation (7) shows expression when renewable resource is not available and energy storage system is supplying power (so acting as generator). Equation (8) presents cost function of one renewable source and Equation (9) is taking account of sum of cost of all renewable sources. Equations (10)–(12) are showing load balance expressions.

User's satisfaction assessment,

$$X_{Id,t} = \frac{CBT_{d,t} - CBT_{d,t-1}}{\Delta t} \tag{13}$$

Where, *CBT* is net break time for load d and $X_{Id,t}$ is state vector at time t. For all user's satisfaction, average accumulation interruption time

$$AvgAIT = \frac{1}{D}\sum_{t=1}^{T}\sum_{d=1}^{D} CBT_{d,t} = \frac{1}{D}\sum_{t=1}^{T}\sum_{d=1}^{D} X_{Id,t}\Delta t \tag{14}$$

To keep the number of interruptions to a minimum for each user,

$$\sum_{t=1}^{T} X_{Id,t} \leq IB_{I,d} \tag{15}$$

For the whole study horizon T, $IB_{I,d}$ is the maximum permissible interruption number for load *d*. The continuous controlled and non-controlled time for load d during period *t* is denoted as $C_{off,dt}$ and $C_{on,dt}$ and can be calculated as,

$$C_{\mathit{off},dt} = \frac{C_{off,d(t-1)} + X_{Id,}\Delta t}{X_{Id,t}} \tag{16}$$

$$C_{on,dt} = \frac{C_{on,d(t-1)} + (1 - X_{Id,})\Delta t}{(1 - X_{Id,t})} \tag{17}$$

In this model, the goal of minimizing operating time is used to limit switching and to ensure and extend the life of load devices.

$$X_{Id,t} - X_{Id,(t-1)}(C_{on,d(t-1)} - T_{on,d,\min}) \geq 0 \tag{18}$$

$$\sum_{i=1}^{T_{\mathit{off},d,\max} - C_{\mathit{off},d,t}} X_{Id,t} \leq (T_{\mathit{off},d,\max} - C_{\mathit{off},g0}) \tag{19}$$

$$\sum_{n=i}^{i+T_{\mathit{off},g,\max}} X_{Id,n} \leq (T_{\mathit{off},d,\max},\ k = 1,\ldots T - T_{\mathit{off},g,\max}) \tag{20}$$

Constraint (18) states that consumer equipment must be on for at least $T_{on,d,\min}$ incessant period before being turned off. Furthermore, interruption time of a load should not be too long in order to ensure user comfort, which is expressed as the $T_{\mathit{off},d,\min}$ maximum continuous load managed duration. Constraint (19) ensures that the initial continuous interruptible time does not exceed the maximum permissible period when assessing the initial cumulative control time of interruptible. Constraint (20) ensures that the total amount of interruptible time during the study period does not exceed the maximum permissible time.

3 Solution Procedure

The proposed solution for the above constrained optimization problem formulation utilizes linear programming relaxation (LPR) method. Subsequently, to compute the improved performance a mixed integer linear programming relaxation (MILPR) technique is also used herein. MILPR method results in improved performance when compared to LPR method. However, the time complexity for MILPR is more when compared to LPR method. MILPR problem is solved using MATLAB and general algebraic modelling system with CPLEX solver. A comparison between iterative complexities is illustrated in Table 3.

The objective of this paper is to ensure minimum cost of energy generation, carbon emission from generation and load side along with user's satisfaction and break time to ensure life span of equipment. Since the carbon emission cut is primary concern in India, so maximum emission tolerance $TE_{\max}$ is used as break point criteria for proposed algorithm.

$$\sum_{k=1}^{N_G}(u_k(P_{k,t}^{(I)})^2 + v_k P_{k,t}^{(I)} + w_k) + \sum_{n=1}^{N} \phi(P_{nd,t}^{(I)} \leq TE_{\max} \tag{21}$$

Where, $P_{k,t}^{(I)}$ and $P_{nd,t}^{(I)}$ are the solutions obtained from Equation (1) after Ith iteration. In India, the value is determined by government rules based on historical emission data and the current emission reduction objective. There are two criteria for stopping iterative process of solution either condition of $TE_{\max}$ met or no of iteration reaches to maximum value set by independent system operator i.e. $I \leq I_{\max}$.

$$I \leq I_{\max} \tag{22}$$

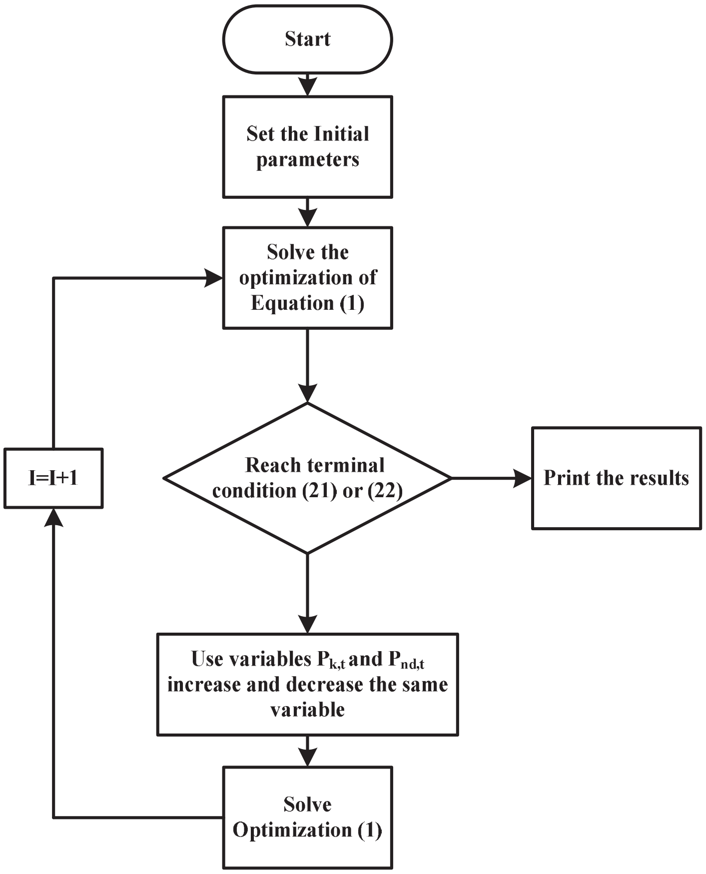

Figure 2 Flow chart of the iterative algorithm for solving optimization.

This optimization problem is a non-linear multi-objective problem. Multi-objective problems rarely have a single global solution [22]. In this case, effective Pareto optimum solutions are applied utilizing linear programming relaxation to meet various constraints. Heuristic optimization algorithms [23–26] can be used to find the Pareto optimal solution.

Figure 2 shows solution process through flow chart. Figure 2 shows that solution procedure will stop by either satisfying condition of Equation (21) or (22). Equation (21) is emphasizing on net carbon emission limit and Equation (22) sets solution based on number of iteration. Equation (22) is taken in to account of condition that if solution is not converging to expected limit of carbon emission.

4 Complexity Analysis of Algorithm

The proposed method utilizes linear programming relaxation method to minimize constrained objective function. The proposed method involves complex mathematical formulation to reach to coveted dispatch with carbon emission reduction as per prescribed limit with load side management. This paper compares complexity in terms of number of iterations used with traditional NSGA-II, improved NSGA-II, LPR and MILPR.

5 Performance Evaluation

5.1 Experimental Conditions

The IEEE-30 bus system network is used to illustrate the usefulness of proposed environment friendly energy-saving dispatch model. Table 1 and Figure 3 shows the cost of operation and parameters of emission function. Table 2 shows cost of operation and parameters of emission function for flexible loads. Rs 12/kg price of carbon emission (approximated) is used based on standard charge in India. $TE_{\max}$ is set as 18000 kg. Table 5 evidently demonstrates that the LPR can create a better optimal solution with best computational performance and the least number of iterations using a multi-objective decision making method based on maximum deviations.

5.2 Experimental Results

Linear programing relaxation (LPR) and mixed integer linear programing relaxation (MILPR) are used to obtain solution of multi-objective optimization problem. The results are shown in Tables 3, 4 and 5. The graphical

Table 1 Emission factors and cost characteristics of thermal units

Thermal Units	*G1*	*G2*	*G3*	*G4*	*G5*	*G6*
At Bus	1	2	13	22	23	27
Min/Max Power (MW)	0/80	0/80	0/40	0/65	0/30	0/55
p_k	0.021	0.0176	0.0624	0.0082	0.026	0.026
q_k	2.05	1.85	1.05	3.20	3	3
r_k	15.31	12.64	18.44	9.45	11.36	12.42
π_k *(Rs/kg)*	6.0	4.9	6.1	5.7	5.3	5.8
u_k	0.01541	0.01378	0.119	0.1199	0.01553	0.183
v_k	1.3741	0.7521	1.2011	0.7063	1.7667	1.4692
w_k	18.6	23.82	20.62	11.9	24.35	27.59

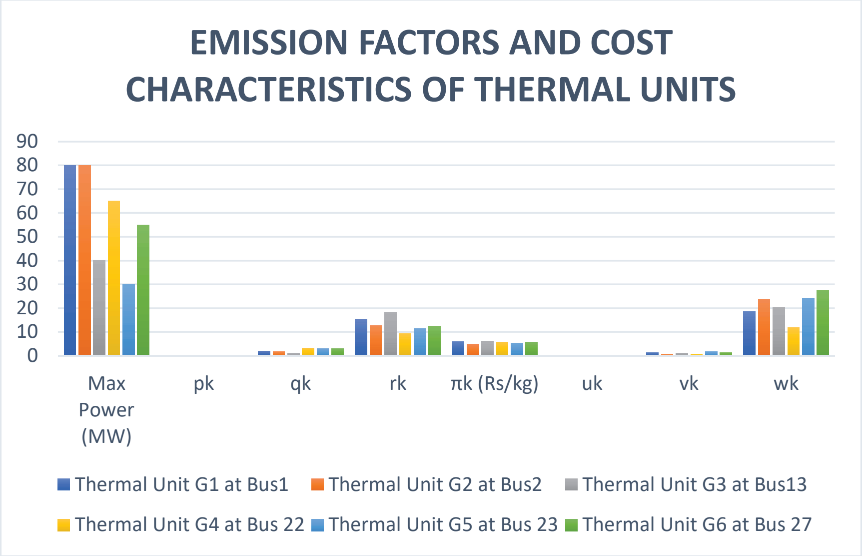

Figure 3 Emission factors and cost characteristics of thermal units.

Table 2 Emission parameters of system flexible loads and operation cost parameters

Load	*L1*	*L2*	*L3*	*L4*
At Bus	2	8	12	21
Initial Power	26.7	35	16.2	23.5
σ_d *(Rs/MWh)*	72.1	88.1	65.2	57.2
Upper limit of interruptible load (MW)	5	7.5	2.5	4.5
Max continuous interruptible time (h)	4	5	6	6
Min continuous running time (h)	6	6	6	6
Initial interruptible time (h)	1	1	0	0
ς_m *(Rs/MWh)*	154.2	17.07	13.11	14.67
Upper limit of incentive load (MW)	4	9	3	4
μ_d	0.8159	0.9637	0.9256	0.8909
ω_d	91.88	94.28	91.66	87.45

representation of results obtained using different methods corresponding to Table 3 is shown in Figure 4. The rate of convergence (RoC) curves for different methods is shown in Figure 5. The solution obtained is compared with traditional NSGA-II and improved NSGA-II in terms of number of iterations needed to reach solution and complexity. From the RoC curves,

Table 3 Comparison among various methods

	Traditional NSGA-II	Improved NSGA-II	LPR	MILPR
No of iterations	15	12	9	8
Optimal value of Objective function (Rs. in thousands)	65880	64017	63982	64273

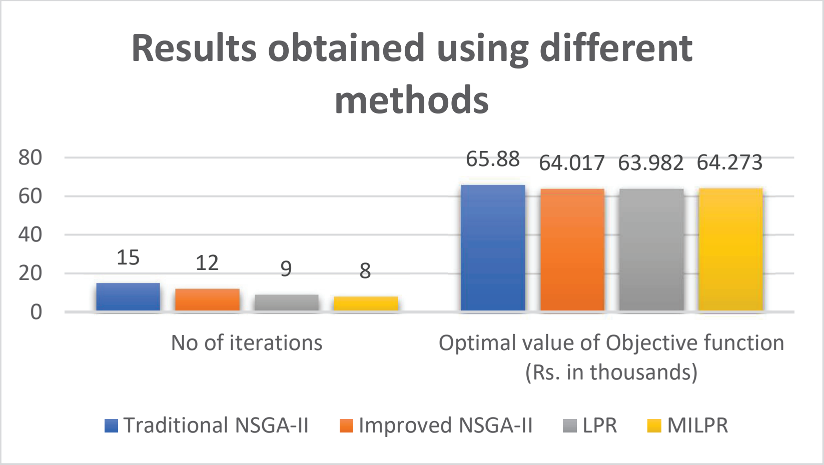

Figure 4 Results obtained using different methods.

Table 4 Values of different function for Emission limit of 18000 kg

Cost Function (Rs)	Emission (kg)	Compensation and Incentive (Rs)	Emission of Loads (kg)	Total Cost (Rs)
76684	54284	47483	9562.8	312504

it can be seen that the presented MILPR has the fastest convergence rate as compared to other presented methods. The number of iterations required by MILPR is the lowest as compared to other schemes and is evident from the Figure 5.

Results with system operation cost, compensation and incentive cost and pollutants emission data is given in Table 4. A clearer observations of the results, obtained for different emission limits, can be visualized from Figure 6. On the other hand, these parameters calculated with various emission limits are shown in Table 5. Effectiveness and iteration complexity shown in Table 3. Results are showing significant improvement by proposed algorithm.

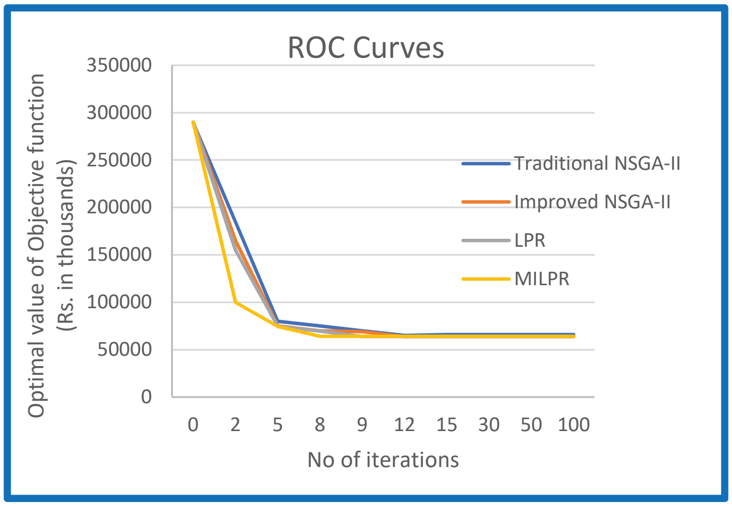

Figure 5 ROC curves for different methods.

Table 5 Optimal solutions for cost functions with various emission limits

	Optimal solution for		
	Emission Limit of 18000 kg	Emission Limit of 17100 kg	Emission Limit of 16200 kg
Cost of System Operation (in Rs.)	76684	74528	73215
Cost of Compensation and Incentive cost (in Rs.)	54284	64282	78389
Cost of Pollutants emission (in Rs.)	15684	14782	14176
Total Cost (in Rs.)	312504	316780	317584

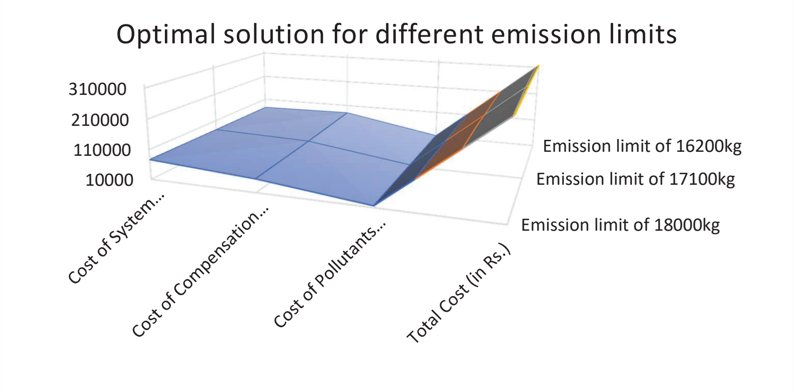

Figure 6 Optimal solution for different emission limits.

6 Result Discussion

This paper presents an algorithm for optimization of operational cost, carbon emission with the consideration of equipment break time to ensure the life span and user satisfaction. This optimization problem considers the constraints pertaining to the system. Combining various function for desired outcome along with constraints forms a non-linear optimization problem. Solution of non-linear optimization problem is difficult because solving non-linear optimization problem is still not a mature technology. In this paper, to solve this problem linear programing relaxation and mixed integer linear programing relaxation used. Presented algorithm implemented on IEEE-30 bus system with cost parameters and emission parameters. Flow chart in Figure 1 shows solution procedure. Solution procedure involves carbon emission limits as parameter to identify the desired result. Table 3 shows iteration complexity comparison with existing methods. Results of various objective function shown in Table 4, which mainly show emission and total cost of operation. Results in Table 5 shows data with various possible change in emission limits. The emission limits changes by 5% and 10% for next two cases.

7 Conclusions

In this paper, an algorithm is proposed for optimizing cost generation function with carbon emission reduction with consideration of load side management with constraint applicable to the system operation. This optimization problem is solved using linear programming relaxation (LPR) and mixed integer linear programming relaxation (MILPR). The presented algorithm produces significant results with less iteration complexity. Various objective function such as operation cost, carbon emission, and load emission have been evaluated. The presented algorithm also tested with maximum possible emission limit. Linear programming relaxation and mixed integer linear programing methods employed to solve the non-linear optimization problem in this paper. Result shows significant improvement over the existing method in term of number of iterations.

In future, this problem may apply non-linear optimization with consideration of renewable penetration into power system network. Further uncertainties parameters may be involved as constraint into system resources.

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