Economic Load Dispatch Considering Renewable Energy Resources

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Abstract— This paper aims to extend knowledge about the performance of Economic load dispatch (ELD) considering renewable energy resources do with wind generation. The main objective of the ELD problems is to determine the optimal combination of power outputs of all generating units to meet the required demand at minimum cost while satisfying the constraint including the load demand balance. A General Algebraic Modeling System (GAMS) is used to minimize the objective function, while satisfying system operating constraints. General Algebraic Modeling System (GAMS) software has been utilized to solve the problem of non-smooth load dispatch by the scheduling of the active power of generators to check the capability of GAMS for non-smooth function and start-up cost based on Unit commitment (UC). The developed algorithm is tested on the IEEE-24 bus reliability test system considering variability in renewable energy sources and load demand. The results demonstrate the feasibility and effectiveness of the developed programming to minimize the total generation cost including the load demand balance.

Keywords: Economic dispatch, Renewable Energy Resources, Unit commitment, General Algebraic Modeling System (GAMS), Constraint, Wind generation

I. INTRODUCTION

In the last decade, to promote competition the electric power industry operation has been converted from vertically integrated to the deregulated environment. In a competitive era, it is the prime responsibility for the system operator to maintain system security with the economy.ELD Generation scheduling allocates generation level of each unit to fulfill load demand at different times by minimizing fuel cost and also to satisfy the operating constraints of the system. In real-time power system operation, the load varies continuously with time horizon which increases violation and reduces security in the power system. In a pool based market mechanism, GENCOs submit their offers to sell their generation while Discoms submit bids to purchase power. In a deregulated scenario, being an independent company, GENCO's main focus is to maximize its profit[1]. While, distribution companies try to purchase power at a minimum rate. Also, demand is continuously changing throughout the day. The load demands are generally higher during the daytime and early evenings when industrial loads are high, lights are on and so forth, and lower during late evenings and in the early morning when almost the population is asleep[2]. It is the core responsibility of system operators to commit enough generating units to meet the load demands in power systems. For better Economic load dispatch it is necessary to commit adequate generating units to balance load demand and turning units off when they are not needed can save a large amount of money [3]. Cost minimization is realized by committing less expensive units while satisfying the corresponding constraints and dispatching the committed units economically[4]. The UC problems of thermal generating units, such as a unit should not be committed more than once in a day or not more than two units of the same plant should be started up simultaneously. This scheduling problem of thermal units is solved using a branch[5]. A short term unit commitment problem solved by a heuristic approach, which replaces an expensive unit in operation is presented in [6]. The commitment schedule generated is compared with a dynamic programming algorithm and found savings on the daily average cost. In the deregulated system operation, the selection of unit commitment problem in generation scheduling is complicated by solving classical optimization techniques, such as augmented Lagrangian relaxation[7], dynamic programming, and the branch and bound algorithm[8]. In day-ahead generation scheduling including ac network security model to incorporate voltages magnitudes which could be a critical factor in real-time power systems operation. In the power system, the system operator used a security-constrained unit commitment program to plan a secure and economic hourly generation schedule. A Lagrange relaxation and dynamic programming tool are used by the system operator to solve the unit commitment problem with security-constrained in[9].

The main objective of ELD is to minimize the total active power generation cost including fuel cost, emission cost, maintenance cost, network losses cost by meeting the following constraints:

- Real power balance
- Network security constraints (maximum MW power flows of transmission lines)
- Downward and upward generator ramp-rate limits
- Lower and upper generation limits of each generating unit
- Prohibited operating zones

Emission rate (SO2, CO2, NOx).

GAMS based programming is developed for economic load dispatch optimization that includes two important functions as unit commitment and economic dispatch. The power system optimization problems are broadly categorized as operation and planning problems. To minimize the total active power generation cost of units while satisfying all constraints. The ELD problem is an essential optimization problem in the electrical power system.

II. PROBLEM FORMULATION FOR ECONOMIC LOAD DISPATCH

The Economic load dispatch problem can be formulated as mixed-integer constrained, where the objective function of a thermal power plant to minimize as follows:

$$\mathrm{f}_1 = minimize\left[\sum_{i=1}^{N} \mathrm{FC}(\mathrm{P}_{ij}) + \mathrm{SC}_{ij}\right] \quad (1)$$

[10]

where $FC(P_{ij})$ and SC_{ij} are the production cost of an ith thermal unit in a jth hour and start-up costs of an ith unit in a jth hour, P_{ij} its power output. The production cost as follows:

$$FC(P_{ij}) = aP_{ij}^2 + bP_{ij} + c \qquad [11] \quad \text{-- (2)}$$

Where, a, b and c are cost coefficient. The start-up cost characteristic as follows:

$$SC_{ij} = u_{ij}(1-(u_{ij})\left[\alpha_i + \beta_i(1-\exp(1-\frac{T_{ij}^{off}}{\tau_i}))\right] \text{-- (3)}$$

Where, α_i, β_i and τ_i is a respectively hot start-up cost, cold start-up cost, and cooling time constant. T_{ij}^{off} is turn off time of ith unit in the jth time. u_{ij} is the status of the unit ith in the jth time. Unequal voltage constraint at each bus generated active power at generator buses and line flow in MVA are included as a penalty factor in the objective function. So, an objective function is generalized as:

$$f_2 = f_1 + j_1(P_g - P_g^{limit}) + j_2(S - S^{limit}) + j_3(V - V^{limit}) \quad \text{-- (4)}$$

Here, j_1, j_2, j_3 are penalty factor and $P_g^{limit}, S^{limit}, V^{limit}$ are limits of the real power generator, line flow, and voltage limit of each bus respectively.

The above objective function is minimized subject to the following constraints:

1) Real power balance constraint: The total thermal power (P_{ij}) must be equal to the total load demand (P_D) and power loss (P_{loss}) in jth transmission lines:

$$\sum_{i=1}^{N} u_{ij}P_{ij} = P_D + P_{loss} \qquad (5)$$

Where, u_{ij} is the status index of the ith unit in the jth period (1 for up and 0 for down). In this work, the transmission power losses (P_{loss}) are computed using the Newton-Raphson AC power flow.

2) Real power operating limits of thermal generating units are:

$$P_g^{min} \le P_g \le P_g^{max} \qquad [11]\ (6)$$

Where, P_g^{min} and P_g^{max} are minimum and maximum generation limits of the generator.

3) Unit minimum up/down (MUT/MDT) time for thermal generating units can be referred to as

$$(T_{i,j-1}^{on} - MUT)(u_{i,j-1} - u_{i,j}) \ge 0 \qquad \text{-- (7)}$$

$$(T_{i,j-1}^{on} - MDT)(u_{i,j} - u_{i,j-1}) \ge 0 \qquad \text{-- (8)}$$

Where, T^{on} and T^{off} are the unit turn on and turn off time respectively.

4) The transmission line constraints are:

$$|S_l| \le S_l^{max} \qquad \text{-- (9)}$$

where, S_l^{max} is the maximum transmission capacity of line in MVA.

5) The ramp rate constraints for thermal generating units are:

$$P_{ij} - P_{ij-1} < UR_i \qquad \text{-- (10)}$$

$$P_{ij-1} - P_{ij} < DR_i \qquad \text{-- (11)}$$

where UR_i and DR_i are the ramp-up and down rate limits of ith unit respectively.

6) Bus Voltage magnitude limits are:

$$V^{min} \le V \le V^{max} \qquad \text{-- (12)}$$

Where, V^{max} and V^{min} are maximum and minimum voltage limits on each bus.

III. SOLUTION USING GENERAL ALGEBRAIC MODELING SYSTEM (GAMS)

General Algebraic Modeling System is created by Alireza Soroudi for Power System Optimization. The main objective of their research was to power system optimization using programming in GAMS for economic load dispatch. The General Algebraic Modeling System (GAMS) is a modeling tool for mathematical programming and optimization purposes. These techniques are robust and have proven their effectiveness in handling many classes of optimization problems.

A. GAMS search area:

Each GAMS model consists of the following main elements: [12]

- Sets: sets are used to define the indices in the algebraic representations of models.
- For example, set of generating units, set of network buses, set of time periods, set of slack buses, etc.
- Data: The input data of each GAMS model are expressed in the form of Parameters, Tables, or Scalars. The parameters and tables are defined over the sets. The scalars are single value quantities.
- Variables: The variables are decision sets and are unknown before solving the model.
- Equations: The equations describe the relations between the data and variables.
- Model and Solve Statements: The model is defined as a set of equations that contain an objective function. The solve statement asks GAMS to solve the model.
- Output: There are several ways to see the outputs of the solved model such as saving them in XLS file and displaying them.

General GAMS code structure and elements are shown in the figure: -1

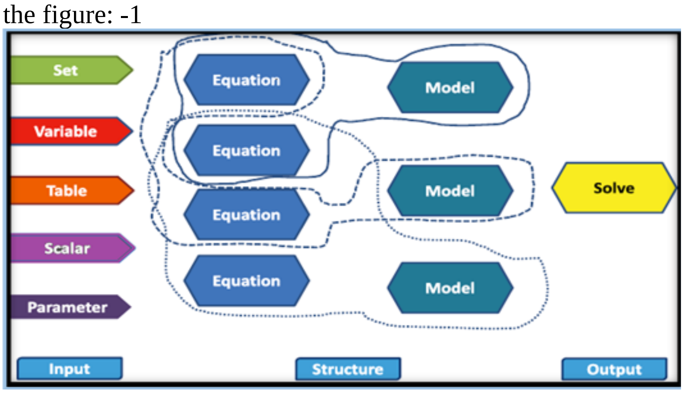

Fig. 1: shown the General GAMS code structure. Various models can be coded in GAMS coding as follows:

LP	linear programming
QCP	Quadratic programming (the model can only contain linear and quadratic terms)
NLP	Nonlinear problem with continuous constraints
DNLP	Nonlinear problem with discontinuous constraints
MIP	Mixed-integer linear programming
MIQCP	Mixed-integer quadratic constraint programming
MINLP	Mixed-integer nonlinear programming

Defining cost-efficient, total power demand, and different variables including generators power output, objective function.

Algorithm for Optimal power flow for economic load dispatch using GAMS:

The GAMS algorithm step by step procedure is as follows:

1) Step:1 Define set values: (Number of Buses, Slack bus, Generator Bus, Time periods)
2) Step:2 Define Scalar values: (Sbase) for per unit calculation
3) Step:3 Define Alias: (bus, node) Set node is defined as the similar set to set bus
4) Step:4 Define GenData: the technical and economic characteristics of generating units
5) Step:5 Define GBconect: the connection point of each generating unit
6) Step:6 Define table BusData: specifies the demand values in each bus
7) Step:7 Define set conex: specifies how each bus is connected to the other network buses
8) Step:8 Define table branch: the branch characteristics
9) Step:9 Define Variable: OF (objective function), Pij (active power flow between bus and node), and delta (voltage angle at each bus)
10) Step:10 Define Equations: {const1(active flow calculation between each pair of connected buses), const2 (nodal active power balance in each bus), and const3 (objective function calculation)

IV. RESULTS AND DISCUSSION

The GAMS based algorithm is implemented on the modified IEEE-24 bus reliability test system. This system consists of 26 generator units, 17 load buses connected by 34 transmission lines and transformers. Here we use three wind generating units in this work and multiple periods ac opf based. The total generation capacity is 3225MW. The data for generators, the percentage of system loads at each bus, and the hourly peak loads are taken from [13]. The generating units connected at bus-13 is considered as slack bus and it is assumed that all three units at this bus are always connected. The voltage limit at each bus is taken constrained between 0.95 p.u and 1.05 p.u. A maximum load for this system is 2850 MW at hour 18 and the minimum load is 1824 MW at hour 5.

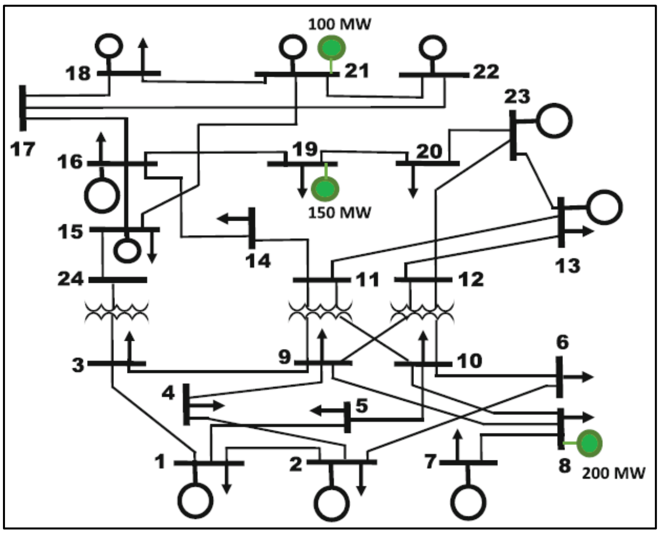

Fig. 2: IEEE 24 bus reliability test power system [14]

To verify the effect of transmission line flow limits on generation inventory, two cases are considered. Case-1: without transmission line limits, Case-2: with transmission line limits. In both cases, a quadratic function as an operating cost and exponential function as a start-up cost function are considered. The thermal power plant uses a quadratic fuel cost function such as the Fuel Cost Curve. The fuel cost curve allows us to look at a wide range of economic dispatch practices such as the total operating cost of a system and minute to minute loading of the generator. The fuel cost function becomes more non-linear when the actual generator response is considered. While a start-up process of the thermal plant depends upon changes in temperature based on the amount of heat supplied from the fuel it follows an exponential decay function with the limit being the temperature of the surroundings, which is typically reached in the range of 48-60 hours. The start-up cost depends exponentially on the number of hours since the thermal unit last shutdown. The committed schedule of the thermal power plant is shown in table-1 to obtain optimal generation cost.

The binary number ‘1’ or ‘0’ represent on and off states of different units at different hours. For large power generation in this system, units 20-26 comprises in table-1 consider as baseload power plants.

A. Case:1 Without transmission line limits:

In this case, the problem of economic load dispatch was solved without considering line flow limits by using GAMS software. It was tested on the IEEE-24 bus reliability test system for different load at a 24 hour time horizon. In this simulation transmission losses are consider and obtain optimal generation cost for different hours by using GAMS shown in fig-(3), results in obtain system total operating cost was $ 7,96,582.07 and, also derived individual active power generation of each unit for the different time period is shown in fig-(4)

Hr	Units (1-26)																									
1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	0	0	1	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
3	1	0	1	1	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1
4	1	1	1	1	0	0	0	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
5	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	1	1	0	0	0	0	0	1	0	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1
7	0	0	1	1	0	0	1	0	0	1	0	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1
8	1	1	1	1	0	0	1	1	0	1	0	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1
9	1	0	1	1	0	0	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
10	0	0	1	1	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1
11	0	0	1	1	0	0	1	0	1	1	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
12	1	1	1	1	0	0	1	1	1	1	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
13	0	1	1	1	0	0	1	1	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
14	1	0	0	1	1	1	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1
15	0	0	1	1	0	0	1	1	0	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
16	0	1	1	1	0	0	1	1	0	0	0	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1
17	0	1	1	1	0	0	1	1	1	0	0	1	1	1	0	1	0	0	0	1	1	1	1	1	1	1
18	0	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1
19	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
20	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
21	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
22	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
23	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
24	0	0	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1

Table-1 Unit commitments

B. Case-2: With transmission line limit on line-23 with 300MW

In this case, a`line flow is reduced to analyze security-constrained of the system and to realizes the effectiveness of the approach method. By reducing line flow in the system, all the generating units have to change their generation to satisfy load demand and to flow active power through the line within the limits. Thus, due to a change in generation, operating cost also changes. So, using an approach method, a new generation is obtained for different load by considering line flow limits and transmission losses for the different time period is shown in fig(5). A-line flow of case-1 and case-2 is shown in table-(2) after reducing the line limit to 300MW. After applying the approach method, It notifies Table 2: That line 23 is overloading which is connected between bus 14 and bus 16 of the system. Further, it also observed that line 23 is not overloading over all the time periods except hour 1 to 9th and 24th hour. Cost comparison of both case-1 and case-2 shown in fig-(6) of an overloading time period

hour	Without line limit	With line limit
1	315.90	297.69
2	316.52	296.48
3	304.08	297.81
4	305.04	296.38
5	305.43	291.71
6	311.05	295.28
7	301.33	284.05
8	320.76	297.99
9	311.46	298.12
24	312.35	297.39

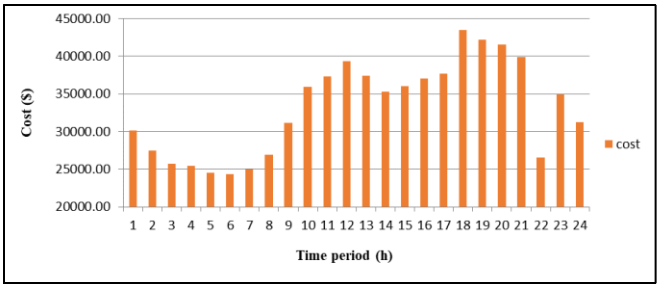

Fig. 3: Hourly cost of generation (without line limits)

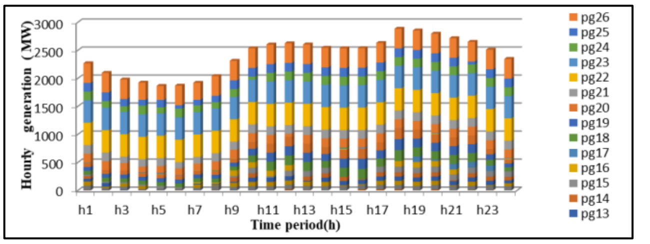

Fig. 4: Comparison of hourly generation (MW)

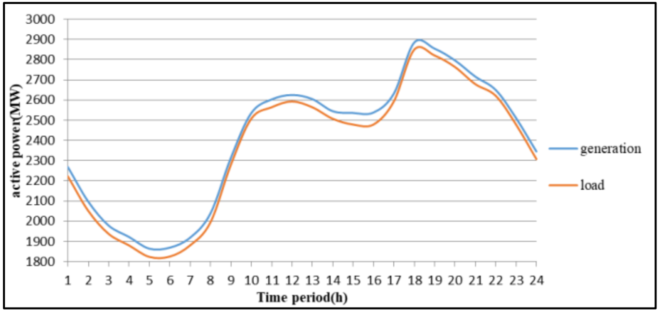

Fig. 5: Comparision between hourly generation and demand

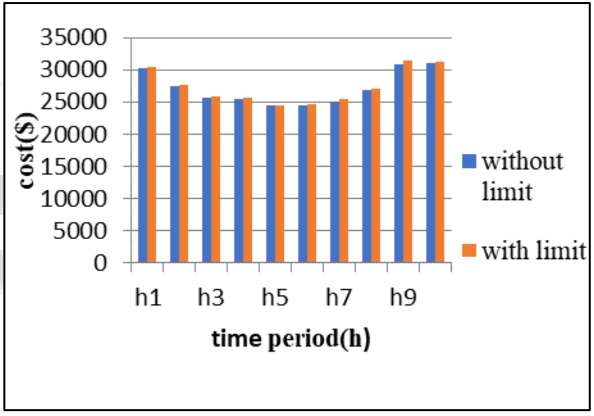

Fig. 6: Cost comparison of without limit and with the limit

Thus, a new generation is obtained by considering all the system constraints and bus voltage constraints. Results of optimization obtain without reporting any violation. A comparison of bus voltage before and after optimization is shown in fig (7), it shows that voltages are better found after optimization.

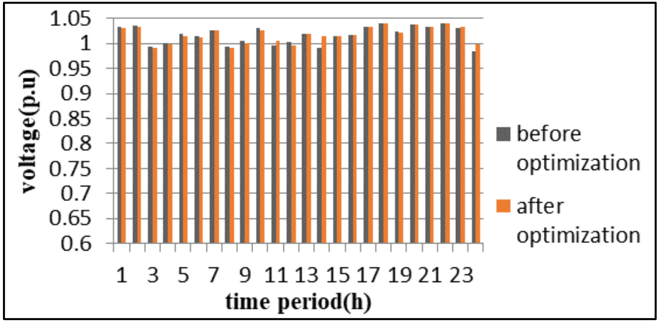

Fig. 7: comparison of bus voltages before optimization and after optimization for 24 time periods.

It indicates that GAMS is best suited for economic by considering all system constraints. Thus, the system operating cost was increased by $ 7,96,145.1 after line limits reduce, which is more as compared to the cost of case-1 without the line limit.

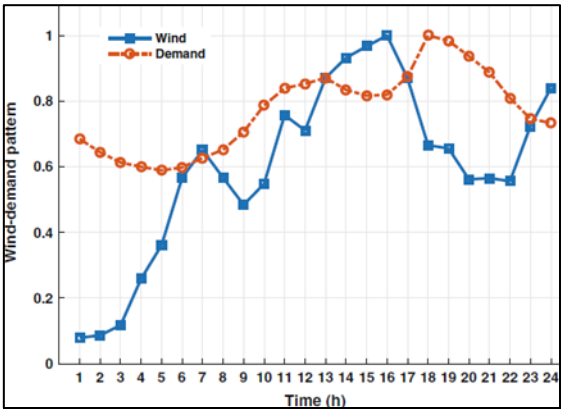

Fig. 8: Wind-demand variation patterns v/s time

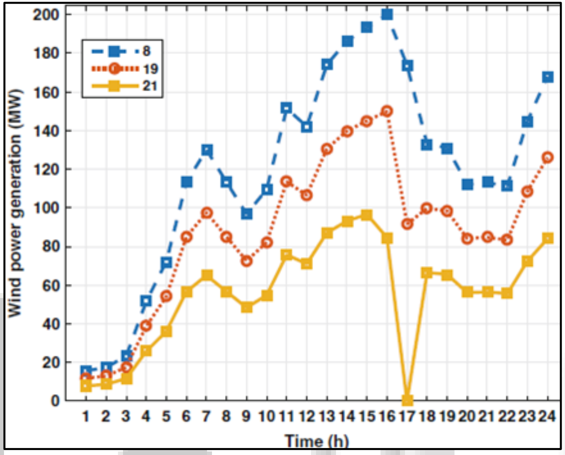

Fig. 9: Windpower generations at efferent buses v/s time

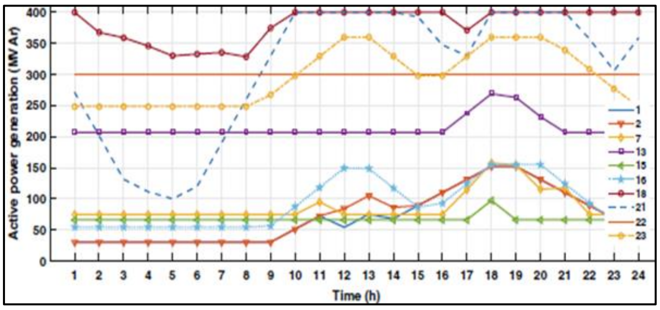

Fig. 10: Active power generation of thermal units in MP-AC OPF

V. CONCLUSION

In comparison with the conventional ELD model, GAMS is presented as a more accurate but complex model that is non-differentiable, non-convex, and multi-modal. A GAMS based algorithm has been developed to solve the short term Economic load dispatch problem. The algorithm is tested on the IEEE-24 bus reliability test system, which consists of 26 thermal generating units. Two cases viz: 1) without transmission line limits and 2) with transmission line limits have been evaluated and optimal solutions are found. This approach may be helpful to the system operator to find the most economical generation schedule in a deregulated environment system by considering 26 generating units and obtained the best generation scheduling. The results show that the proposed method was indeed capable of obtaining a higher quality solution efficiently in ELD.

A. *Results in GAMS:*

Bus	1	2	3	4	5	6	7	8	9	10	11	12	13
Pg(MW)	152	152	0	0	0	0	257.15	0	0	0	0	0	206.85
Load(MW)	108	97	180	74	71	136	125	171	175	195	0	0	265
Cost($/hr)	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
δ (rad)	-0.151	-0.151	-0.113	-0.185	-0.191	-0.230	-0.105	-0.186	-0.136	-0.172	-0.044	-0.0.31	0.000
14	15	16	17	18	19	20	21	22	23	24		Total Generation	
0	167	155	0	400	0	0	400	300	660	0		2850	
194	317	100	0	333	181	128	0	0	0	0		2750	
20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7		496.80	
0.027	0.182	0.168	0.251	0.276	0.146	0.164	0.291	0.399	0.187	0.069			

B. *Compare Results:*

	Bus	1	2	3	4	5	6	7	8	9	10	11	12	13
Pg GAMS	Pg(MW)	152	152	0	0	0	0	257.15	0	0	0	0	0	206.85
Pg PSO	Pg(MW)	145	115	0	0	0	0	222	0	0	0	0	0	195
	Cost GAMS(Rs/hr)													
	Cost PSO													

14	15	16	17	18	19	20	21	22	23	24	Total generation

0	132.26	155	0	400	0	0	400	300	660	0	2850
194	317	100	0	333	181	128	0	0	0	0	2578
25.78	16.00	15.68	15.79	15.85	16.86	17.87	15.89	15.85	18.42	17.19	37260
0.012	0.158	0.149	0.230	0.255	0.131	0.152	0.269	0.378	0.177	0.049	49550

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