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OPTIMAL LOAD SCHEDULING OF THERMAL POWER PLANTS BY UNIT COMMITMENT METHOD

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Abstract: - In present days, the increase in load demand is enormous and with interconnection of networks it is essential to run the generating stations with in its constraints to meet the load demand optimally and reduce the real power generation cost. A major objective for the thermal power generation is to reduce fuel consumption by scheduling optimal power generation to each unit (economic dispatch) such that each generating unit is within its equality and inequality limitations. The optimum real power generation scheduling plays crucial role in scheduling power of utility power system. Because power saving is prior. For huge multi-unit power station, reasonable unit dispatch is nearly related to the running economy of it. The unit commitment on thermal power economic dispatch has been analyzed in this paper. Primarily unit commitment optimization model which can eliminate frequent starts and stops is done. Then, load scheduling of thermal power plants based on constraint limits to reduce fuel cost is analyzed. The solution methodology includes algorithm for unit commitment method and economic load scheduling of thermal power plants in its constraints. The results are simulated in Mat Lab for 3 generators, 6 generators, 15 generators supplying for certain loads.

Key Words: Economic Load Dispatch (ELD), Lagrangian Multiplier (λ), Generation Scheduling (GS), Unit Commitment (UC), Cost of Power Generation (C (P_G))

1 Introduction

The recent developments in restructured electric power systems provide an opportunity for electricity market participants, such as GENCOs, TRANSCOs, and DISCOs, to exercise least-cost or profit-based operations. However, the system security is still the most valuable aspect of the power system operation, which cannot be overlooked in the Standard Market Design (SMD). [1].

Unit Commitment (UC) is a decision-making process executed by utilities, independent system operators (ISOs), and other system operators to ensure minimal-cost production schedules for thermal fleets. While variants of UC have been used in practice since the 1970s, models and algorithmic techniques for computing UC schedules have changed drastically over the years. Present large-scale coordination of optimization problem is the focus of significant, active research due to the real power cost savings. [2]. In order to supply high-quality electric power to customers in a secured and economic manner, thermal unit commitment (UC) is good because it also generates bulk power. It is thus recognized that the optimal UC of thermal systems, which is the problem of determining the schedule of generating units within a power system, subject to device and operating constraints results in a great saving for electric utilities. So the general objective of the UC problem is to minimize system total operating cost while satisfying all of the constraints. [3]. Large-scale thermal power units must adopt effective strategies to reduce energy consumption and improve the utilization hours in order to create more benefits and survive and develop in the present fierce competition. Carrying out economic dispatch which can help to optimize the units' operation level, reduce coal consumption and reduce emissions is an effective way to reduce power generation cost and enhance competitiveness. Economic dispatch problem consists of two parts, one is unit commitment and the other is optimal load distribution. [4].

Optimal load dispatch is of the best considerable optimization problems in power systems engineering. The main objective of economic load scheduling concept is to determine the generation schedule that minimizes the total cost of generation while satisfying a required load demand and some other system operating constraints. The predominant types of generating plants are the nuclear, hydro and thermal generators. Nuclear plants tend to operate at a nearly constant output power level; the operating costs of hydro plants do not vary significantly with power output, but thermal units have operating costs which vary significantly with power output. The total cost of real generation of a thermal unit consists of the fixed costs and variable costs. The purpose of unit commitment (UC) is to optimize schedules of thermal unit operation for a given time interval in a way which minimize system operating costs. With the scale of power system growing rapidly and the implement of the new competitive business environment, the requirements become rigorous for the solution of the UC problem. The real power demand is usually high during daytime and early evening because factory loads are high, increased domestic load and reduces during the late time in evening and early morning hours because load considerations are less. In addition, the electric power usage has a weekly cycle, the power consumption being lower over non-working days than working days. This is considered as unit commitment issue, and is analyzed as an idea to schedule generators commercially in a power system in order to meet the demand of load from hot & cold spinning reserve. In practical this issue is considered over some periods of time, like one day, one week, and a month. [5].

Unit commitment (UC) in power systems involves the proper scheduling of the on/off states of all the units in the system. In addition to fulfill a large number of constraints, the thermal power plants with optimal unit commitment (UC) should meet the load demand plus the spinning reserve requirements regularly at every time interval such that the total real power generation cost is minimum. The UC is a combinatorial optimization problem with both binary and continuous variables. The number of combinations of 0–1 variables grows exponentially as being a large-scale problem. Therefore, UC and load scheduling is one of the most complex task in power systems. [6]. The Unit Commitment (UC) and load scheduling i.e., Economic Load Dispatch (ELD) are well known problems in the power industry and have the potential to save millions of rupees per year in fuel and related costs. For any real time system this analysis is a composite resolution-making process and it is difficult to develop any rigorous mathematical optimization methods capable of solving the UC-ELD problem. Also, multiple constraints should be imposed which must not be violated while finding the optimal or near-optimal solution. [7]. The purpose of present time is mainly on optimizing the running cost of power generating stations. In the present consequence, meeting the real power load as well as optimizing generation schedule has become important. The exact solution of the Unit Commitment Problem can be obtained by analyzing all generating units' capacity, constraints, cost of real power generation & all feasible combinations [8]. A literature view on unit commitment undoubtedly says that several techniques have been evolved to solve unit commitment (UC) along with economic load dispatch. They include dynamic programming method; which is a stochastic search method that explore for answer from one state to the other. The practical states are saved. The earliest optimization-based method is Dynamic programming to be appealed to the UC problem. The main advantage of UC is being accomplished to answer problems of a large variation of sizes and to be easily adjusted to represent characteristics of certain utilities. The drawback of this method is the computational attempts enlarge exponentially as the number of units & problem proportion increases and solution is impossible and its exploration of minimum up and downtime constraints and time relying start-up costs is suboptimal. [9].

2 Problem Formulation

2.1 Unit Commitment: (UC)

Unit commitment can be clarified as the generator selection that should be utilized to meet the load demand economically that has low fuel cost, for the system forecasted over a period of time. The Unit Commitment Problem (UCP) determines a minimal cost turn-on and turn-off planning of a number of electrical real power generating units to encounter a load demand during satisfying a set of running constraints. It is a well-identified problem in power industry that aids in reducing fuel cost if units are accomplished correctly so that fuel cost is saved. [9]

Requirements for UC:

a) Satisfactory generating units will be accomplished to supply the load.
b) Reduction of power loss or fuel cost.
c) The most economic unit can be generated to supply the load unit operating function to its superior efficiency.

Factors considered in UC:

a) To locate the nature of differing load and also to commit the units based on a graph that is pinched between load demand and hours of work.
b) The hot reserve and cold reserve possible numbers of units that are committed to meet the load.
c) Calculating the load dispatch for all feasible combinations and also operating limits of the units.

Unit Commitment is analyzed as a complex optimization problem which schedule real power generating units to minimize the objective function (cost of real power generation) in the presence of heavy constraints. [11]

The objective function to minimize *Total cost of real power generation = Fuel cost for thermal unit + Start-up cost for unit + Shut down cost of unit*

A typical input-output characteristic also called fuel cost curve of a thermal generating unit is convex as shown in Fig. 1. The X axis can be represented with Rs/Hr or Btu/hr and Y axis is represented with output P_G. (P_G is the real power generated)

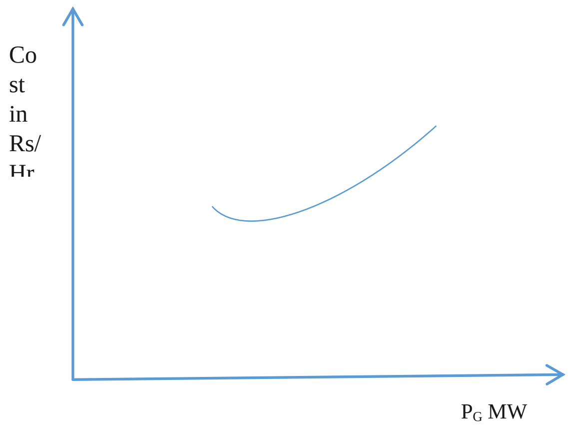

Fig. 1: Input-output characteristics

The thermal power generating sections have a non-linear cost outcome *Ci*. The contrast of fuel cost of thermal unit is stated by a quadratic polynomial equation.

$$Ci = a_i P_{Gi}^2 + b_i P_{Gi} + d_i \ldots(1)$$

here a_i is to consider losses in the system, b_i is for fuel cost and d_i is the payment and emolument, interest and devaluation.

The economic load scheduling of thermal power plants for optimal load dispatches is such that the total electric real power generation equals the load demand plus transmission line real power losses, which can be mentioned

$$\sum_{i=1}^{n} PGi - PD - Pl = 0 \ldots (2)$$

n = total number of generating plants,
PGi = real power generation of ith plant, PL = total transmission line loss, PD = total load demand.

The inequality constraints is given by

$$P_{GiMin} \geq P_{Gi} \geq P_{GiMax} \quad \ldots\ldots (3)$$

Maximum real power generation P_{GiMax}
Minimum real power generation P_{GiMin}

The slope of this input-output curve is called the incremental fuel cost of unit. [10]

Start- up cost: When the thermal unit is at rest (hot & cold reserve units), some energy is required to bring the unit online to be connected to take load. It is the maximum for the unit at cold start (cold reserve unit). The startup cost for cold reserve unit is more than hot reserve unit.

Shut down cost: It is the cost required for closing down the unit. Periodically during the closing period, the cost can be disregarded if boiler may be allowed to cool down naturally.

The two costs startup and shut down are as shown, and are compared while determining the UC schedule and a best approach among them is chosen [9].

Startup cost for cold reserve unit,:

$$S_C = C_S(1-\varepsilon^{(-t/\alpha)}) F + (\text{ Fixed cost}) \ldots..(4)$$

Startup for hot start:

$$S_C = C_{temp} Ft + (\text{ Fixed cost}) \ldots\ldots.(5)$$

Where S_C is the startup cost, *Cs* is the cold start cost in MBtu, *F* is the fuel cost, fixed cost that includes crew expenses and maintenance expenses, *Ctemp* is cost in Mbtu/hour for maintaining the unit at operating temperature, α is the thermal time constant of the unit and *t* the time in hours the unit was allowed to cool. Shutdown cost is generally taken as a constant value. [9]

Constraints in unit commitment [12]:

Power balance: the total generated load and demand at corresponding hours must be equal

$$\sum_{i=1}^{n} PGi = PD \ \ldots\ldots\ldots\ldots\ldots \ (6)$$

Where PGi is real thermal power generation of i th plant, n is the number of thermal generating units and PD is the total load demand

Minimum capacity committed: It is the total real power available from all elements synchronized on the system minus present load demand plus the transmission line losses.

$$\sum_{i=1}^{n} PGimax \geq PD + Ploss \ \ldots\ldots\ldots..(7)$$

Where PGimax is the maximum power generation of ith plant, Ploss is the active power loss.

Thermal constraints: The transposition and pressure of thermal power units increase gradually after starting. So they must be synchronized before bringing online. Must run thermal units: Some of the thermal station generators must be given a must run status in order to supply voltage support for the power system. For such units U_i=1.

Minimum up/down time:

$$T_i^{ON} \geq T_i^{up} \quad \ldots\ldots\ldots (8)$$
$$T_i^{Off} \geq T_i^{down} \quad \ldots\ldots\ldots (9)$$

3 Methodology

3.1 Unit commitment algorithm:

i) Choose the required combination of n no of generators, Combination = 2n-1
ii) Select the feasible combination according to the given load.
iii) Calculate the combination having least production cost.
iv) Compute total cost, and do for all states.
v) Save lowest cost strategies.
vi) Trace optimal schedule

After unit commitment, the objective of optimal load scheduling of thermal power plants is to assign the real power generated from each unit in a plant for a given load so that fuel cost or real power generation is minimum subjected to equal and inequality constraints. Here, optimum generation scheduling to load is achieved by a technique, an iterative and an accurate method to determine output of generator. An algorithm to optimal scheduling of real power generation and minimize fuel cost are iteratively solved on the following steps for a particular load demand.

The computational procedure is as follows:

1. Start
2. Initially chose $\lambda=\lambda_{0,}$ this value should be chosen properly, such that the value should be more than the highest obstruct of the incremental fuel cost of the various generating units. Calculate P_{G1}, P_{G2},,P_{Gi} based on equal incremental cost.
3. Assume $P_{GI} = 0.0$; i=1,2,…………N
4. Read the thermal unit constants *ai*, *bi*, loss coefficient matrices [B matrix]
5. Calculate the real power generation at all buses using

   $$P_{Gi}=(1-B_{0i}-b_i/\lambda-\sum_{j=i}^{k} 2BijPGj)/(2a_i/\lambda+2B_{ij}) \quad i=1,2,\text{-------},k \qquad \text{............} (10)$$

   The prices of real powers to be replaced on the RHS of Eq.(6) until iteration equate to the values calculated in step 2. For succeeding iterations the values of real powers to exchange matches to the powers in the antecedent iteration. However if any thermal unit disobey the limit of generation then that generator is stable at the violated limit.
6. Check if the real power generation and load demand differences at all generator buses linking 2 successive iterations is less than the identified value,

   Otherwise go back to step 2.
7. Verify if real power balance equation is satisfied,

   $$\sum_{i=1}^{n} PGi - PD -< \in \text{......} (11)$$

   if yes, stop. else, go to step-8.
8. Increase λ by Δλ; if

   $$\sum_{i=1}^{n} PGi - PD < 0 \text{.................................} (12)$$

   decrease λ by Δλ; if

   $$\sum_{i=1}^{n} PGi - PD - Pl > 0 \text{.............} (13)$$
9. Repeat from step 5
10. Renovate λ as $\lambda^{(k+1)} = \lambda^{(k)} - \Delta\lambda^{(k)}$ where λ is the step size
11. Stop

4 Systems Analyzed

Here we consider three test systems. At first 3 generators are considered with their cost curve equations (second order polynomial expression). The unit's committed and optimal real power generation scheduling of 3 thermal generating units for different loads are determined and also cost of real power generation for different loads is determined. The price for economic allocation of real power generation to each generating unit is determined and whether all units are satisfying its equality and in equality limitations are confirmed. In the second system, 6 generators with their cost curve expression are considered (second order polynomial equation). The optimum real power generation scheduling for different load conditions with unit commitment is explained here. In the third system, 15 generators are considered with their cost curve expression (second order polynomial equation). The optimum generation scheduling for certain load conditions with unit commitment is explained here.

CASE STUDY-1:

Here the generators cost curve expressions are considered with second order polynomial expressions. A 3 plant system with the following cost equations considered, are shown in the table 4.1 [10]

TABLE 4.1
DATA FOR COST CURVE

Ci	ai	bi	di
1	0.00525	8.663	328.13
2	0.00609	10.040	136.91
3	0.00592	9.760	59.16

The data in table 4.1 specifies the second order polynomial expressions in the form $C_i=a_iP_{gi}^2+b_iP_{gi}+d_i$. The coefficients used to specify the value of λ.

The inequality plant capacity constraints i.e .the generator's real power boundaries are given in table 4.2.

TABLE 4.2
GENERATOR LIMITS

Gen	Min. MW	Max. MW
1	50	250
2	5	150
3	15	100

The data in table 4.2 specifies the minimum and maximum limits for generating units. The limits specify that the units should operate within its specified limits. If the generating unit generates active power above or below its specified limits, the cost of generation of active power of all units will be high compared to optimum generation.

CASE STUDY-2:

Here the generators cost curve expressions are considered with second order polynomial expressions. A 6 plant system with the following cost equations considered, are shown in the table 4.3

TABLE 4.3
DATA FOR COST CURVE

Ci	ai	bi	di
1	0.005	2	100
2	0.01	2	200
3	0.02	2	300
4	0.003	1.95	80
5	0.01	1.45	100
6	0.01	0.95	120

The data in table 4.3 specifies the second order polynomial expressions in the form $C_i=a_iP_{gi}^2+b_iP_{gi}+d_i$. The coefficients used to specify the value of λ.

The inequality plant capacity constraints i.e .the generator's real power boundaries are given in table 4.4.

TABLE 4.4
GENERATOR LIMITS

Gen	Min. MW	Max. MW
1	10	200
2	10	200
3	10	200
4	10	200
5	10	200
6	10	200

The data in table 4.4 specifies the minimum and maximum limits for generating units. The limits specify that the units should operate within its specified limits. If the generating unit generates active power above or below its specified limits, the cost of generation of active power of all units will be high compared to optimum generation.

CASE STUDY-3:

Here the generators cost curve expressions are considered with second order polynomial expressions. A 15 plant system with the following cost equations considered, are shown in the table 4.5 [10]

TABLE 4.5
DATA FOR COST CURVE

Ci	ai	bi	di
1	0.000299	10.1	671
2	0.000183	10.2	574
3	0.001126	8.8	374
4	0.001126	8.8	374
5	0.000205	10.4	461
6	0.000301	10.1	630
7	0.000364	9.8	548
8	0.000338	11.2	227
9	0.000807	11.2	173
10	0.001203	10.7	175
11	0.003586	10.2	186
12	0.005513	9.9	230
13	0.000371	13.1	225
14	0.001929	12.1	309
15	0.004447	12.4	323

The data in table 4.5 specifies the second order polynomial expressions in the form $C_i=a_iP_{gi}^2+b_iP_{gi}+d_i$. The coefficients used to specify the value of λ.

The inequality plant capacity constraints i.e .the generator's real power boundaries are given in table 4.6.

TABLE 4.6
GENERATOR LIMITS

Gen	Min. MW	Max. MW
1	150	455
2	150	455
3	20	130
4	20	130
5	150	470
6	135	460
7	135	465
8	60	300
9	25	162
10	25	160
11	20	80
12	20	80
13	25	85
14	15	55
15	15	55

The data in table 4.6 specifies the minimum and maximum limits for generating units. The limits specify that the units should operate within its specified limits. If the generating unit generates active power above or below its specified limits, the cost of generation of active power of all units will be high compared to optimum generation.

TABLE 4.7
GENERATION OF ACTIVE POWER

S. NO	LOAD DEMAND (P_{DT}) MW	COST OF GENERATION RS/HR
1	170	2138.8
2	250	2829.6
3	300	3365.1
4	500	5696.3

5 Results and Analysis

Here we present solutions for unit commitment and optimal load organizing for three test systems. The thermal units' committed and optimal generation organizing of thermal power plants for different loads is determined and also cost of generation for different loads is determined. The price of real power generation for economic allotment of generation to each generating unit is determined and verified whether all units are satisfying its equality and in equality constraints.

CASE STUDY-1:

For the data shown in tabular columns generator cost expression table 4.1, generator limits table 4.2, the units committed for optimal generation scheduling along with cost is shown for certain load conditions.

TABLE 5.1
UNITS COMMITTED FOR CERTAIN LOADS AND LAMDA (Λ) VALUE

SL NO	P_{DT} (MW)	U1	U2	U3	LAMDA VALUE
1	170	1	1	1	11.9
2	250	1	0	1	11.5
3	300	1	0	1	11.4
4	500	1	1	1	15

TABLE 5.2
OPTIMUM GENERATION ALLOCATION OF 3 GENERATING UNITS FOR DIFFERENT LOADS

SL NO	P_{DT} (MW)	P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)
1	170	136.6037	5	28.4915
2	250	181.6389	-	68.4298
3	300	208.1363	-	91.9283
4	500	250.0000	150	100

Optimal generation scheduling for 3 generators for dissimilar burden conditions is shown in table 5.1 & 5.2. Table 5.1(a) shows results for different load conditions for three generating units and values of λ. Table 5.2 shows the optimum generation allocation to other thermal generating units for different load demands. From the tabular column shown it is clear that all thermal generators are operating within its constraint limitations. It means that all generators are functioning economically (low fuel cost). The generation of real power for different generating units is varied based on load demand but within its constraint limits. So it says all generators are operating optimally and cost of real power generation is not too high.

CASE STUDY-2:

For the data shown in tabular columns generator cost expression table 4.3, generator limits table 4.4, the units committed for optimal generation scheduling along with cost is shown for certain load conditions. [13]

TABLE 5.4 UNITS COMMITTED FOR CERTAIN LOADS AND LAMDA (Λ)

S NO	P_{DT} (MW)	U1	U2	U3	U4	U5	U6	LAMDA VALUE
1	215	0	0	0	1	0	1	3.3183
2	355	0	0	0	1	0	1	3.1605
3	598	1	0	0	1	1	1	3.7444
4	666	1	0	0	1	1	1	4.3089
5	780	1	0	0	1	1	1	4.7951
6	980	1	1	1	1	1	1	7.5218

TABLE 5.5 (A) OPTIMUM GENERATION ALLOCATION FOR DIFFERENT LOADS

S NO	LOAD DEMAND (P_{DT}) MW	COST OF GENERATION RS/HR
1	215	657.2306
2	355	1097.9
3	598	1923.9
4	666	2179.7
5	780	2685.5
6	980	3849.6

TABLE 5.5 (B)
OPTIMUM GENERATION ALLOCATIONS FOR DIFFERENT LOADS

S NO	P_{DT} (MW)	P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)
1	215	0	0	0
2	355	0	0	0
3	598	159.0319	0	0
4	666	193.0459	0	0
5	780	200.000	0	0
6	980	200.0000	142.8827	71.4413

TABLE 5.6
COST OF GENERATION FOR DIFFERENT LOAD DEMANDS

SL NO	P_{DT} (MW)	P_{G4} (MW)	P_{G5} (MW)	P_{G6} (MW)
1	215	126.9682	0	88.0905
2	355	200.000	0	155.000
3	598	200.0000	107.016	132.016
4	666	200.0000	124.0229	149.0229
5	780	200.0000	180.0904	200.000
6	980	200.0000	170.3827	195.3827

Unit commitment for certain loads along with lamda values and optimal generation allocated for six generators for various load conditions is shown in table 5.4 & 5.5(a,b). Table 5.4 shows results units committed for certain loads and lamda (λ) values and table 5.5 (a,b) shows the optimum generation allocation to generating units for different load demands. From the tabular column shown it is clear that all generators are functioning within its constraint limitations. It considers that all generators are functioning economically (low fuel cost). All the generators from data in table 4.2 specifies that $10 \leq P_{gi} \leq 200$, it means that minimum operating limit of all generators is 10 MW and maximum operating limit for all generators is 200 MW. Now the cost for generation to meet different load demands is shown in table 5.6

CASE STUDY 3:
For the data shown in tabular columns generator cost expression table 4.5, generator limits table 4.6 for certain load, units committed and optimal generation allocation for 15 generating units are shown here. For the load demand 2970 MW, the optimum scheduling results are shown in table 5.7.

TABLE 5.7
UNIT COMMITMENT AND COST OF GENERATION FOR CERTAIN LOAD

Generating unit	Unit commitment	Optimum Power generated in MW	
1	1	455	Total load demand 2970 MW
2	1	455	
3	1	130	
4	1	130	
5	1	470	
6	1	460	
7	1	465	Total cost of generation 34927 Rs/hr
8	1	60	
9	1	25	
10	1	160	
11	1	80	
12	1	80	
13	0	0	
14	0	0	
15	0	0	

6 Conclusion

This paper deals with unit commitment of thermal power plants to reduce the price of real power generation to optimally schedule the real power to meet load demand. Each thermal power plant equality and inequality boundaries are considered to analyze optimum generation scheduling. From all test cases it is clear that all generators work within its constraint limitations (maximum & minimum) for optimum generation allotment or economic load scheduling. If the generators are not operated within its constraint limitations whether below its min generation capacity or above its max generation capacity economic load scheduling is not possible (price of real power generation). The price of real power generation is less for same load capacity when unit commitment is considered. Therefore unit commitment provides better chances for economic operation of power systems in thermal power plant scheduling.

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