ADDITIVE AND DIVISIVE CLUSTER ALGORITHM FOR COST REDUCTION IN UNIT COMMITMENT

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ABSTRACT

This paper presents a novel technique to solve the problem of unit commitment through sorting of units into different clusters. This sorting is implemented in order to decrease the overall operating cost and to assure the various constraints that involve minimum up/down. Unit commitment problem is an important optimization task in daily operational planning of power systems which can be mathematically formulated as a large scale nonlinear mixed-integer minimization problem. A new methodology employing the concept of cluster algorithm called as additive and divisive hierarchical clustering has been employed in order to carry out the technique of unit commitment. Proposed methodology involves two individual algorithms. While the load is increasing, additive cluster algorithm has been employed while divisive cluster algorithm is used when the load is decreasing. The proposed technique is tested on a system with generating units in range of 10-100 and the performance of the proposed technique has been reported through simulation results.

Keywords: *unit commitment, additive clustering, divisive clustering*

1. INTRODUCTION

The technique of Unit Commitment (UC) involves the calculation of levels of generation pertaining to generating units and their commitment for a certain interval of time in order to reduce the operational cost. It is actually a significant issue with very good impact on the economics. The generalized problem of UC is well known in the electric industry and its efficient solution definitely has the ability to save huge money each year with respect to costs of fuel and other expenses. It is basically an area that involves the scheduling of production which relates to the calculation of status of the units that are generating power for various intervals of time in order to meet the load and other requirements which are actually dependent on the environmental issues, equipment and the system. Generally the problem of UC is a process that involves making complex decisions and it is tough to design optimization techniques that are capable of solving the system in real time. The various multiple constraints also need to be considered while determining the correct commitment schedule [1].

The most often discussed deterministic mathematical programming techniques include: Branch-and-Bound [2], Dynamic Programming [5,6], Priority List [3,4], Lagrange Relaxation [7–9], and Mixed- Integer methods [10]. Generally all these mathematical techniques are quite fast and are much simple to be implemented but most of them suffer from the problem of numerical convergence and have the following limitations [1]: (i) They do not guarantee the convergence to optimum point globally for non-convex problems such as UC. (ii) The results also are inconsistent due to the various approximations considered while solving the constraints and objective functions which are nonlinear. (iii) The difficulty in reaching the solution due to the consideration of various constraints.

In order to overcome the general difficulties in various approaches, a novel method with the application of cluster algorithms has been proposed in this paper. The method uses Additive and Divisive Cluster Algorithms. The proposed methodology can be unfolded into three stages. In the first stage, four clusters are formed namely base load, intermittent load, semi-peak load and peak load clusters. All the generating units of the plant are segregated into corresponding clusters based on operating costs. In the second stage, UC solution is obtained by developing Additive Cluster (AC) algorithm for increasing load pattern. Finally in the third stage a Divisive Cluster (DC) algorithm is developed for decreasing load pattern.

The remaining paper is organized as follows: Section 2 deals with problem formulation; General purpose additive cluster and divisive cluster algorithms are discussed in the Section 3. Simulation results and discussions are carried out in Section 4 and finally conclusions are drawn in the Section 5.

2. PROBLEM FORMULATION

Based on the concept of minimization of the cost-objective function in the unit commitment problem, certain units are stated to be as ‘ON’ and remaining as ‘OFF’. The following are the various notations considered during the implementation of the problem

N : Quantity of generating units in the system
T : Time for which the system is running in hours (h);
i : Count of Unit (i = 1,2,….., N);
t : Count of time (t = 1,2,….., T);
$I_i(t)$: status of i^{th} unit at t^{th} hour (is considered as 1, if the Unit is ON; or 0, if the unit is OFF);
$P_i(t)$: Power Generation of i^{th} unit at t^{th} hour;

P_i^{max}, P_i^{min}: Values corresponding to Maximum / Minimum power output (MW) of i[th] unit;
$D(t)$:Load demand at t[th] hour;
$R(t)$:Reserve capacity of the system at t^{th} hour;
T_i^{on} :Minimum up time limit of i[th] unit;
T_i^{off} : Minimum down time limit of i[th] unit;
$X_i^{on}(t)$:Time for which the i[th] unit is continuously ON;
$X_i^{off}(t)$:Time for which i[th] unit is continuously OFF;
$SC_i(t)$: Start-Up cost of i[th] unit;
$FC_i(t)$:Cost of Fuel of i[th] unit;
RU_i : *Ramp up rate of unit i*
RD_i : *Ramp down rate of unit i*
TC: Total Cost for generation;
HC(i): Hot start cost of i[th] unit;
CC(i): Cold start cost of i[th] unit;
CS(i): Cold start hour of i[th] unit;
τ: Time Step of Unit Commitment: 60 min
a_i, b_i, c_i: cost coefficients of Fuel

Objective Functions

The main objective of the problem of UC is to minimize the Total cost (TC) which consists of various components of FC and SC represented by:

$$\text{Min } (TC) = \sum_{t=1}^{T}\sum_{i=1}^{N}(FC_i(t)\cdot I_i(t)+SC_i(t)) \tag{1}$$

Where Fuel cost of i^{th} unit:

$$FC_i(t) = a_i + b_i P_i(t) + c_i P_i(t)^2 \tag{2}$$

and Start-up cost

$$\begin{aligned} SC_i(t) &= HC(i): if\ T_i^{off} \le X_i^{off}(t) \le H_i^{off}(t) \text{ or} \\ &= CC(i): if\ X_i^{off}(t) \ge H_i^{off}(t) \end{aligned} \tag{3}$$

$$\text{where } H_i^{off}(t) = T_i^{off} + CS(i) \tag{4}$$

System Constraints

The constraints, that need to be taken into view while performing the process of optimization of UC are listed below.

Demand of Load

All the units that have been committed need to generate the power that is the same as load demand given by:

$$D(t) = \sum_{i=1}^{N} P_i(t) \tag{5}$$

Spinning Reserve

In order to sustain the reliability of the system during sudden changes of load, the system should be able to contain sufficient amount of spinning reserve capacity.

$$\sum_{i=1}^{N} I_i(t)\cdot P_i^{max} \ge D(t) + R(t) \tag{6}$$

Power Limits of Generators

The output power of each generator should satisfy the criterion given by:

$$P_i^{min} I_i(t) \le P_i(t) \le P_i^{max} I_i(t) \tag{7}$$

Ramp up/down Rates

The power generation of various units is limited by the following operating limits which are time dependent

$$\begin{aligned} P_i^{max} I_i(t) &= \min\left\{P_i^{max} I_i(t), P_i I_i(t-1) + \tau\cdot RU_i\right\} \\ P_i^{min} I_i(t) &= \max\left\{P_i^{min} I_i(t), P_i I_i(t-1) - \tau\cdot RD_i\right\} \end{aligned} \tag{8}$$

Minimum Up/Down Time

Once the commitment of the unit is done, there should be a minimum time before it is to be de-committed given by.

$$T_i^{on} \le X_i^{on}(t) \text{ or } T_i^{off} \le X_i^{off}(t) \tag{9}$$

3. PROPOSED METHODOLOGY

The technique of Cluster Algorithms (CA) can be stated as, to divide a given group of objects into a number of groups or clusters in order that the objects in a particular cluster would be similar among the objects of the other ones. In the first stage of CA, an attempt is made to place an N object in M clusters according to some criterion additive to clusters. Once the criterion is selected, CA searches the space of all classifications and finds the one that satisfies the optimization function.

The proposed methodology for UC problem considers two clustering techniques: Additive Clustering Technique and Divisive Clustering Technique. In the first type of cluster technique, initially individual data points are treated as clusters. Based on necessary criteria (nearest operating costs of units) successively two closest clusters are merged until there is only one cluster remains.

Basic Additive Clustering Algorithm

Step-1: Compute operating cost (proximity) matrix;
Step-2: Repeat;
Step-3: Merge two closest clusters based on least distance value;
Step-4: Update the proximity Matrix to reflect the proximity between the new cluster and the original clusters;
Step-5: Until Only one cluster remains.

In the Divisive type clustering technique, successively each cluster is separated from the others until a singleton cluster of individual point(s) remain. A suitable methodology is required to take the decision on which cluster must be removed from the others. The basic algorithm is given below.

Basic Divisive Clustering Algorithm

Step-1: Compute operating cost (Proximity) Matrix;
Step-2: *Repeat;*
Step-3: Separate a cluster from other clusters based on maximum distance value;
Step-4: Update the proximity Matrix to reflect the proximity between the clusters those remaining;
Step-5: *Until* all the clusters are removed.

The flowchart for the above methodology can be observed from Fig. 1.

The proposed methodology can be unfolded in to three stages.

- In this stage objective cost function of each unit is obtained by evaluating the Euclidian Costs involving Average Fuel cost and Start-up Cost. Priority list of units is prepared based on the minimum objective cost functions and clusters are formed.
- The pattern of load variation on the plant is a cycle of increasing and then decreasing takes place. Two separate algorithms are designed for load increasing pattern and for decreasing pattern. In this stage, an algorithm based on additive clustering technique is developed for increasing load pattern.
- This stage presents an algorithm for UC solution for the decreasing load condition. The algorithm is designed based on divisive clustering technique.

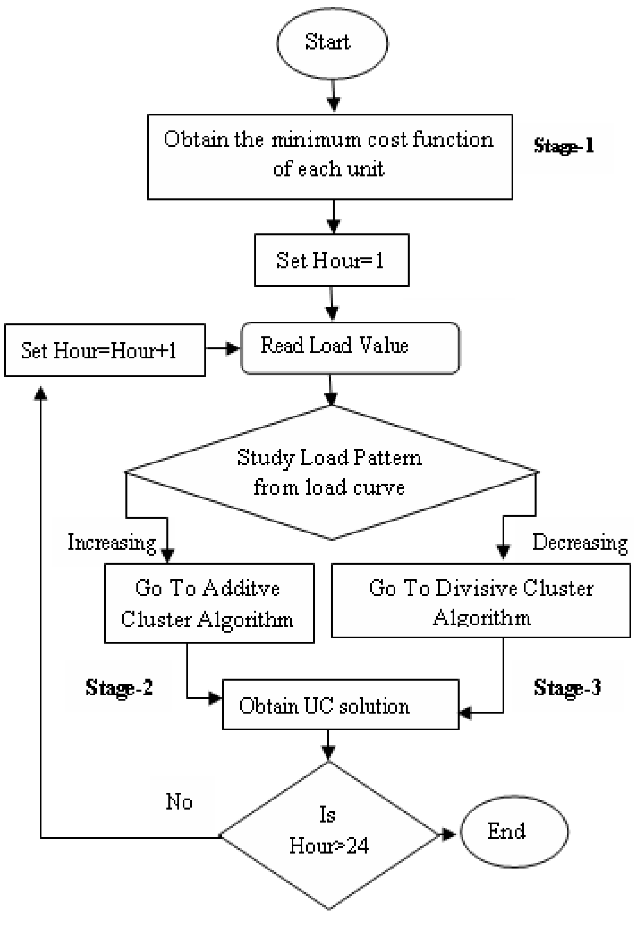

Fig. 1 Methodology of additive and divisive cluster algorithm

The operating cost of each plant is calculated and the plants are clustered based on their objective function values. In this way best clusters are brought out so that they can be employed to take up the load.

Characterization of Various Units

The units that tend to operate for long periods of the day can be seen as generators relating to Base Load (BL) and Intermittent Loads (IL) which generate maximum amount of power. Ideally, it is to be noted that these units need to have minimum value of fuel cost, maximum capabilities of generation but generally they consist of higher start-up costs and start up times since that are ‘‘ON” during most of the working period. Additionally it can be observed that the reliability of the system is dependent on the performance of these units only. The units that have low start up costs and low start up times can be seen as Semi-Peak Load (SPL) and Peak load (PL) units since they can be brought into ‘‘ON” position and ‘‘OFF” position very frequently. As a result it can be observed that these units have low capabilities of generation and high costs as they are connected to the system for loads which are above base load and intermittent load. Based on the generation cost functions, the closet cost function units are segregated into clusters as BL, IL, SPL and PL as given in Table 5.
BL: Load upto800MW duration: 0-24 hours
IL: Load between 800MW to 1200 MW, duration 0-18 hours
SPL : Load 1200MW to 1400 MW, duration 0-6 hours
PL : Load 1400MW to 1500MW, duration 0-3 hours
The maximum limits for the four loads as:
BL-Max: 1000 MW; IL-Max: 1200 MW; SPL-Max: 1400 Mw and PL-Max: 1500 MW.

For carrying out the additive cluster algorithm, objective function values are stored in ascending order and for divisive cluster algorithm the objective function values are stored in the descending order as given in table 4. The closest values are divided into four clusters as BL, PL, Semi PL and IL.

Design of Additive Clustering (AC) Algorithm

Step-1: Read the load value *D(t)*. Spinning Reserve requirement *R(t)*. Threshold values of four clusters.
Step-2: From the load duration curve, identify the load as any: BL, IL, SPL or PL.
Step-3: Commit the units in corresponding cluster by executing subroutine for Economic Dispatch (ED).
Step-4: Check the constraint: D (t) +R (t) < Cluster Threshold value. If condition is satisfied, go to main program. Else, go to next step.
Step-5: Merge next priority list cluster to previous cluster.
Step-6: Go to Step-4;
Step-7: Return.

Design of Divisive Clustering (DC) Algorithm for UC Problem

This DC algorithm is proposed for UC when the load is decreasing after it stopped from increasing. The DCA starts at the point where some units in various clusters are already under ‘on’ condition. Now the requirement is to put some units under 'off' condition, so as to meet the present D(t). The priority list is prepared based on the startup time/costs. The strategy is, to put off the unit with maximum generation cost.

Step-1: Read the system load.

Step-2: De-Commit the next unit with maximum generation cost according to priority list.

Step-3: Commit the units in corresponding cluster by executing subroutine for Economic Dispatch (ED).

Step-4: Check the constraint: D(t)+R(t) sum of all generations. If condition is satisfied, go to main program. Else, go to step-2.

Step-5: Return.

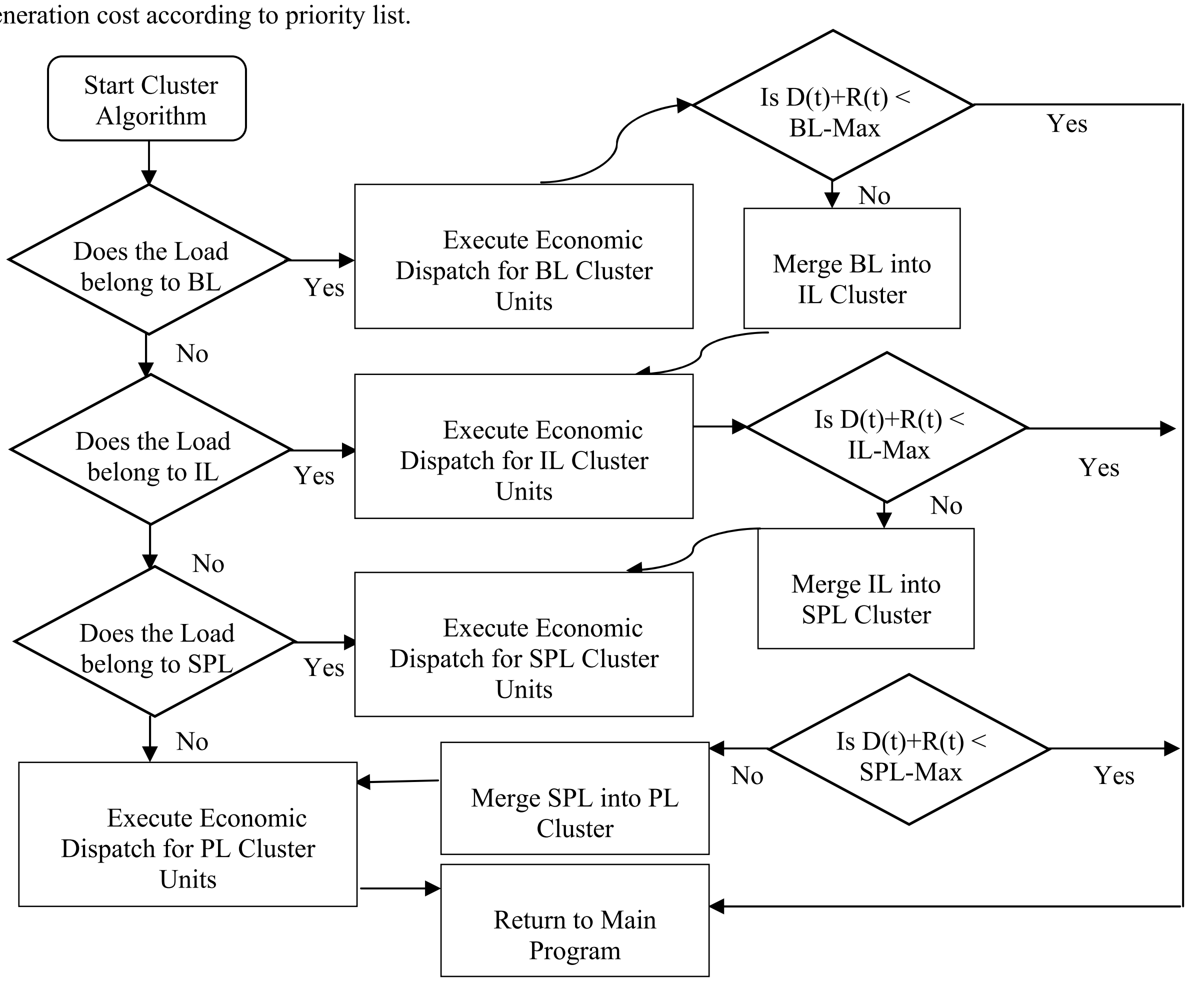

Fig. 2 Proposed Algorithm for UC problem

4. RESULTS AND DISCUSSIONS

Table 1 shows the daily load pattern on the plant and Table 2 shows the operating characteristics of all the plants.

The average fuel costs (A) and start-up costs (B) for all the units can be calculated as follows:

A=Average fuel cost of system= $\dfrac{a_i + b_i p_{i\max} + c_i p_{i\max}^2}{p_{i\max}}$

B=Average start-up cost= $\dfrac{HC(i)}{p_{i\max}}$

The Euclidian costs of all the units can be calculated as follows:

Euclidian costs of the unit =

$\sqrt{(A_i - A_{low})^2 + (B_i - B_{\max})^2}$

The above calculations of all the units have been tabulated in Table 3 and Table 4 respectively.

Table 1 Daily load pattern on the plant

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	700	5	1000	9	1300	13	1400	17	1000	21	1300
2	750	6	1100	10	1400	14	1300	18	1100	22	1100
3	850	7	1150	11	1450	15	1200	19	1200	23	900
4	950	8	1200	12	1500	16	1050	20	1400	24	800

Table 2 Unit characteristics and coefficients

Unit No. (i)	1	2	3	4	5	6	7	8	9	10
P_i^{max}(MW)	455	455	162	130	130	80	85	55	55	55
P_i^{min}(MW)	150	150	25	20	20	20	25	10	10	10
a_i	1000	970	450	680	700	370	480	660	665	670
b_i,	16.19	17.26	19.7	16.5	16.6	22.26	27.74	25.92	27.27	27.79
c_i	0.00048	0.00031	0.00398	0.00211	0.002	0.00712	0.00079	0.00413	0.00222	0.00173
T_i^{on}	8	8	6	5	5	3	3	1	1	1
T_i^{off}	8	8	6	5	5	3	3	1	1	1
HC(i) ($)	4500	5000	900	560	550	170	260	30	30	30
CC(i) ($)	9000	10000	1800	1120	1100	340	520	60	60	60
CS(i)	5	5	4	4	4	2	2	0	0	0
Ini.State	8	8	-6	-5	-5	-3	-3	-1	-1	-1

Table 3 Average fuel cost and start-up cost of each unit

Unit No	1	2	3	4	5	6	7	8	9	10
A	18.606	19.533	23.123	22.005	22.245	27.455	33.454	38.147	39.483	40.067
B	9.8901	10.989	5.5556	4.3077	4.2308	2.125	3.0588	0.54545	0.54545	9.8901

Table 4 Euclidian cost of all units

Unit No	1	2	3	4	5	6	7	8	9	10
Euclidian cost	1.0989	0.92672	7.0654	7.4962	7.6754	12.525	16.833	22.157	23.343	23.867

Table 5 Priority list is formed with minimum operation cost

Priority Order	1	2	3	4	5	6	7	8	9	10
For ACA	2	1	3	4	5	6	7	8	9	10
For DCA	10	9	8	7	6	5	4	3	1	2

Table 6 Segregation of 10 units into clusters and their priority

Cluster type	Base load	Intermittent load	Semi peak load	Peak load
Priority units in the cluster	1,2	3,4,5	6,7	8,9,10

Table 5 shows the priority order of various units corresponding to their Euclidian costs with respect to additive clustering and divisive clustering and Table 6 shows the segregation of all the 10 units in order to take up the daily load pattern. For the 20-generating unit system, the data of the ten generating unit system was duplicated and the load data was multiplied by 2. Similar procedure has been implemented for evaluating the data for 40 unit, 60 unit, 80 unit and 100 unit system. Table 7 shows the allocation of generation to various units based on the daily load pattern and based on the clusters. It can be observed from the table that the clusters only take up the load allotted to them while the other generators do not take up the load until it falls into the other category. The operating costs of the generators taking the load can be observed from the table. It can be observed that the technique is quite simple and easy to be implemented. Table 8 also shows the allocation of various units under various loads for large scale system extending from 20 units to 100 units along with their operating cost.

Table 7 Generation of 10 units in 24 hour schedule

S. No	Load (MW)	Commitment schedule 1	2	3	4	5	6	7	8	9	10	Operational cost ($)
1	700	342.4	357.5	0	0	0	0	0	0	0	0	14644.8
2	750	362.0	387.9	0	0	0	0	0	0	0	0	15623.4
3	850	370	159	162	130	29	0	0	0	0	0	18766.9
4	950	455	159	162	130	29	0	0	0	0	0	20479.6
5	1000	334.1	344.8	162	130	29	0	0	0	0	0	21563.4
6	1100	373.40	405.5	162	130	29	0	0	0	0	0	23522
7	1150	393.02	435.9	162	130	29	0	0	0	0	0	24515.4
8	1200	424	455	162	130	29	0	0	0	0	0	25519.3
9	1300	455	455	162	130	29	29	34	0	0	0	28605.8
10	1400	455	455	162	130	29	29	34	0	0	0	28605.8
11	1450	455	455	162	130	130	29	34	19	19	19	34194.6
12	1500	455	455	162	130	130	77	34	19	19	19	35299.3
13	1400	455	455	162	130	29	29	34	0	0	0	28605.8
14	1300	455	455	162	130	29	29	34	0	0	0	28605.8
15	1200	424	455	162	130	29	0	0	0	0	0	25519.3
16	1050	353.78	375.2	162	130	29	0	0	0	0	0	22538
17	1000	334.1	344.8	162	130	29	0	0	0	0	0	21563.4
18	1100	373.40	405.5	162	130	29	0	0	0	0	0	23522
19	1200	424	455	162	130	29	0	0	0	0	0	25519.3
20	1400	455	455	162	130	29	29	34	0	0	0	28605.8
21	1300	455	455	162	130	29	29	34	0	0	0	28605.8
22	1100	373.40	405.5	162	130	29	0	0	0	0	0	23522
23	900	420	159	162	130	29	0	0	0	0	0	19766
24	800	381.6	418.3	0	0	0	0	0	0	0	0	16611.3
Total Operating cost												**584325**

Table 8 Division of units into clusters and their priority

No. of Generating units	**Base load**	**Intermittent load**	**Semi peak load**	**Peak load**	**Total operating cost**
10	1,2	3,4,5	6,7	8,9,10	**584325**
20	1,2,11,12	3,4,5,13,14,15	6,7,16,17	8,9,10,18,19,20	1167650
40	1,2,11,12,21,22, 31,32	3,4,5,13,14,15,24, 25,33,34,35	6,7,16,17,26,27, 36,37	8,9,10,18,19,20,28, 29,30,38,39,40	2236150
60	1,2,11,12,21,22, 31,32,41,42,51,52	3,4,5,13,14,15,24, 25,33, 34,35,43,44,45,53, 54,55	6,7,16,17,26,27, 36,37,46,47,56,57	8,9,10,18,19,20,28, 29,30,38,39,40,48, 49,50,58,59,60	3505950
80	1,2,11,12,21,22, 31,32,41,42,51, 52,61,62,71,72	3,4,5,13,14,15,24, 25,33, 34,35,43,44,45,53, 54,55,63,64,65,73, 74,75	6,7,16,17,26,27, 36,37,46,47,56,57 ,66,67,76,77	8,9,10,18,19,20,28, 29,30,38,39,40,48, 49,50,58,59,60,68, 69,70,78,79,80	4668600
100	1,2,11,12,21,22, 31,32,41,42,51,	3,4,5,13,14,15,24, 25,33,	6,7,16,17,26,27, 36,37,46,47,56,	8,9,10,18,19,20,28, 29,30,38,39,40,48,	5844175

	52,61,62,71,72, 81, 82,91,92	34,35,43,44,45,53, 54,55,63,64,65,73, 74,75,83,84,85,93, 94,95	57,66,67,76,77, 86, 87,96,97	49,50,58,59,60,68, 69,70,78,79,80,88, 89,90,98,99,100	

5. CONCLUSIONS

A novel method based on clustering technique has been proposed to mitigate Unit Commitment problem. The proposed method is more realistic and less heuristic. Following load pattern, two individual algorithms based on Additive and Divisive cluster algorithms are proposed for increasing and decreasing load patterns. The Euclidian cost of generation of units is obtained and based on these costs the units are segregated in to clusters. Two separate priorities lists one for increasing and another for decreasing load conditions are prepared based on generation costs. A thermal system in the range of 10-100 units has been considered for simulation study. The strategy employed proved to be quite effective and satisfactory as evident through simulation results.

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