HYDRO-THERMAL COMMITMENT SCHEDULING IN A LARGE POWER SYSTEM BY TABU SEARCH METHOD

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Abstract: *This paper presents a new approach for developing a hybrid algorithm for solving the Unit Commitment Problem (UCP) in a Hydro-thermal power system. Unit Commitment is a nonlinear optimization problem to determine the minimum cost turn on/off schedule of the generating units in a power system by satisfying both the forecasted load demand and various operating constraints of the generating units. Tabu search (TS) is a powerful optimization procedure that has been successfully applied to a number of combinatorial optimization problems. It avoids entrapment at local optimum by maintaining a short term memory of recently obtained solutions. The memory structure assists in forbidding certain moves that deteriorates the quality of the solution by assigning Tabu status to the forbidden solutions. The Tabu status of a solution can be overruled if certain conditions are satisfied expressed in the form of Aspiration Level. Aspiration Level (AL) adds flexibility in Tabu Search by directing the search towards attractive moves. The effectiveness of the proposed hybrid algorithm is proved by the numerical results shown comparing the generation cost solutions and computation time obtained by using Tabu Search Algorithm with other methods like Evolutionary Programming and Dynamic Programming in reaching proper unit commitment.*

Key words: *Unit Commitment, Dynamic Programming Method, Evolutionary Programming, Tabu Search.*

1. Introduction

Unit Commitment Problem (UCP) [1-3] is a non-linear combinatorial optimization problem, which is used in power systems to properly schedule the on/off status of all the generating units in the system. The ultimate goal is to determine the minimum cost turn ON and turn OFF of power generating units to meet the load demand in addition to satisfying various operating constraints of the generating units. For large power systems the problem of unit commitment has generally been difficult to solve because of the complex and uncertain nature of the problem. The operating constraints of the generating units make the problem highly non-linear to solve. There are other problems of inconsistency that affect the overall economic operation of the power station. The exact solution of UCP can be obtained by a complete enumeration of all feasible combination of generating units which would be a huge task.

The growth in the demand for electricity forced to introduce many power systems like steam, hydro, nuclear, thermal, tidal and so on. The interconnection of different power systems reduces the cost of generation required to meet the power demand. When the size of the power systems is larger, it is essential to interconnect them to operate the systems economically. Thermal and hydro power systems are often interconnected to meet the demand. The thermal system unit commitment and hydro power generation are to be determined to meet the demand at each hour. The hydro plant reduces the load applied to the thermal system thereby reducing the number of units required to meet the demand with remaining units under shut down. This reduces the fuel cost of the thermal power system and in turn reduces the total operating cost [31].

The real practical barrier is solving UCP is the high dimensionality of the possible solution space. Research endeavors have been focused on developing efficient algorithms that can be applied to large power systems and have less memory and computation time requirements. A number of numerical optimization techniques have been employed to solve the complicated UCP. The different categories being used to solve UCP include Classical methods like the Dynamic Programming (DP), the Lagrangian Relaxation (LR), the Mixed Integer Linear Programming (MILP), the Decomposition Approach (DA), the Benders Decomposition Approach (BDA), the Fuzzy Logic Approach (FLA), the Hopfield Approach (HA), the Tabu Search Method (TSM), the Tabu Search and Decomposition Method (TSD), the Genetic Algorithm (GA), the Evolutionary Programming (EP), the Ant Colony Method (ACM), the Hybrid Approach (HA), the Profit Based Approach (PA). The major limitations of the numerical techniques are inability to handle problem dimensions, large computation time, more memory space and complexity in programming.

The proposed two-stage method [1] has smaller computational requirements than that of the Simulated Annealing algorithm. The optimal generation from hydro and thermal resources is computed simultaneously in the two stage algorithm; there is no need for assuming constant operation of some reservoirs **as** in the Simulated Annealing method. No discretization of state and control variables is needed in the proposed method. The required storage as well as computing time in the proposed method are reduced as compared to those in the successive-approximations algorithm. The results [2] revealed that the partial open-loop feedback control policy provided somewhat higher average and standard deviation for hydroelectric generation in all simulations performed. The higher standard deviation provided, however, not being compensated for by a slightly higher average generation, lead to higher final operating costs. The closed-loop feedback control policy was more efficient in the synthetically simulations. This advantage, however, reduced with the historical simulations, when the different control policies led to almost equivalent performances.

The proposed LR-DP method [3] is efficiently and effectively implemented to solve the UC problem. The proposed LR total production costs over the scheduled time horizon are less than conventional methods especially for the larger number of generating units. The augmented Lagrangian approach [4] presented in this paper accommodates further for pumped-storage units and line flow limitations and concurrently can produce accurate scheduling results. The approach produces feasible schedules and requires no iteration with economic dispatch algorithms. The LR approach [5] to solve the short-term UC Problems was found that it provides faster solution but it will fail to obtain solution feasibility and solution quality problems and becomes complex if the number of units increased. The overall results obtained by the implemented Lagrangian relaxation approach [6] are of very good quality and they are reached within little iteration. We feel that the proposed method could be of help for the solution of UC of hydrothermal power generation systems in the uncertain environment of the competitive electricity markets. The results revealed that the proposed method [7] is very effective in reaching an optimal generation schedule. The potential to determine a more nearly optimal solution to the hydrothermal scheduling problem by using the proposed method.

Test results and numerical experiences show that the proposed solution technique [8] can give a near-optimal or optimal solution for the MILP problem in an acceptable time. The solution of the short term hydrothermal problem not only provides MW schedules for hydro units and plants, but also indicates the hydro unit commitment statuses while minimizing the unit startup costs. The proposed MILP model allows to accurately represent most of the hydroelectric system characteristics, and turns out to be computationally solvable for a planning horizon of one week, proving the high efficiency of modern MILP software tools, both in terms of solution accuracy and computing time [9]. With the proposed [10] distributed implementation, even a small-sized generation company can perform overnight large Monte Carlo simulations on the company's personal computers exploiting their idle times under a simple hydrothermal problem communication protocol.

The upper and lower bound estimates of the optimal value of the objective function are available with each iteration; a feasible solution to the original problem is available with each iteration; prior experience and feasible existing schedules can be directly incorporated into the computational procedure, introducing additional exclusion rules to improve t he efficiency of the restricted integer algorithm [11]. The MIP methods [12] for solving the unit commitment problems fail when the number of units increases because they require a large memory and suffer from great computational delay. The presented decomposition scheme [13] is simple, pure, and robust, even for dominant hydraulic power systems. It is also easy to implement, because it uses well-known, optimized, fast techniques, such as MIP and ac OPF algorithms. The chosen decomposition of the problem allows considering the network's entire modeling, with little impact on computing CPU time. Complex hydraulic chains or additional constrains can be easily modeled and/or added. In our studies [14], reductions in the overall CPU time to solve the problem depended on the case, with a minimum reduction of two times as compared to the classical Multi Stage Benders Decomposition approach and four times as compared to the single linear program approach.

This work [15] builds a fuzzy rule base with the use of the area control error and rate of change of the error. The simulation results show that the proposed fuzzy logic based controller yields improved control performance than the dual mode controller.

The heuristic search algorithms are efficiently used to commit fuel constrained units, pumped-storage units, and repairing violations due to ramp rate and transmission constraints. The proposed method [16] obtains less production costs and faster computational time than Augmented Hopfield Neural Network and hybrid Lagrangian relaxation and quadratic programming.

TS [17-18] is a powerful, general-purpose stochastic optimization technique, which can theoretically converge asymptotically to a global optimum solution with probability one. But it will take much time to reach the near-global minimum.

The TSD [19] has considered the time varying start-up costs as well as the non-linearity in the hydrothermal systems. It can be used as post processor for existing generation scheduling methods or in cases where rescheduling of units is required due to change in the system status. And the application of the modified Benders decomposition method is to solve with constraints that are difficult to formulate. In order to obtain the better results, the experience of the operators in applying some system specific conditions has been included in the Tabu Search method. The proposed approach by this paper can be used in conjunction with the other optimization method to pursue a more comprehensive feasible solution if the initial solutions obtained by other optimization methods fail to satisfy some specific constraints.

The simulation results [20] reveal that the features of easy implementation, convergence in an acceptable time, and highly optimal solution in solving the unit commitment problem can be achieved. GA [21] is a general-purpose stochastic and parallel search method based on the mechanics of natural selection and natural genetics. It is a search method to have potential of obtaining near-global minimum. And it has the capability to obtain the accurate results within short time and the constraints are included easily. The proposed

GA [22], using new specialized operators, have demonstrated excellent performance in dealing with this kind of problem, obtaining near-optimal solutions in reasonable times and without sacrificing the realism of the electric and economic models. Developed algorithms provide optimal unit commitment and also optimal MW values for energy, spinning reserve and non-spin. Presented algorithm and analysis could be beneficial to GENCO with big number of generators to maximize the profit and bid in competitive electricity market [23].

With this new approach [24], decomposition into sub problems for the hydro and the thermal system is not necessary. Numerical experiments with a hydrothermal test system demonstrate the ability of the proposed method to solve the complex optimization problem with its wealth of constraints. Its [25] performance compares favorably with constructive DP which is known to be faster than standard LP. It can be used for a rapid approximate optimal scheduling for large scale complex system with multiple cascaded and pumped storage. Results [26] show that with quadratic thermal cost and without prohibited discharge zones, all EP-based algorithms converge faster during initial stages while Fast EP and Classical EP slow down in the latter stages compared to Improved Fast EP. Improved Fast EP performs the best amongst the three in solving this problem in terms of execution time, minimum cost, and mean cost.

From test results [27], they have demonstrated the feasibility of ACM in the hydro-generation scheduling study. This method is also suitable to be implemented under a parallel computer system. The solution speed can be thus further improved. There is no obvious limitation on the size of the problem that must be addressed, for its data structure is such that the search space is reduced to a minimum; No relaxation of constraints is required; instead, populations of feasible solutions are produced at each generation and throughout the evolution process; Multiple near optimal solutions to the problem involving multiple constraints and conflicting objectives can be obtained in a reasonable time with the use of heuristics; It works only with feasible solutions generated based on heuristics, thus avoiding the computational burden entailed by the GA methods which first generate all feasible solutions and then purge the infeasible ones [28]. The flexibility in the demand constraint both in terms of possibility of buying and selling in the market gives better indication of the likely future scenarios so that better bidding strategy can be made [29].

More improvements could be made to the proposed algorithm in order to increase the speed convergence of the algorithm [30] and its execution time by improving the gradient method, and by adjusting adequately the penalty weight factor.

From the surveyed research works it can be understood that solving the UCP gains high significance in the domain of power systems. Solving the UCP by a single optimization algorithm is ineffective and time consuming. Hence, we are proposing a UCP solving approach based on TSM which provides an effective scheduling with minimum cost. An IEEE test system consisting of 4 hydro generating units and 10 thermal generating units has been considered as a case study and the results obtained are compared with different tabu list and sizes and with the trial solutions.

2. Problem Formulation

The main objective of UCP is to determine the on/off status of the generating units in a power system by meeting the load demand at a minimum operating cost in addition to satisfying the constraints [31] of the generating units. The problem formulation includes the quadratic cost characteristics, startup cost of thermal power system and operating constraints of thermal and hydro generating units. The power generation cost for thermal power system is given in (1a).

$$F_{s,it}(P_{s,it}) = A_i + B_i P_{s,it} + C_i P_{s,it}^{\ 2} \quad \textit{(Rs/hr)} \qquad (1a)$$

where,

A_i, B_i, C_i - The Cost Function parameters of unit i (Rs/hr, Rs/MWhr, Rs/MW^{2}hr).

$F_{s,it}(P_{s,it})$ - The generation cost of unit i at time t (Rs/hr).

$P_{s,it}$ - The output power from unit i at time t (MW).

The overall objective function [9] of UCP that is to be minimized is given in (1b)

$$F_T = \sum_{t=1}^{T} \sum_{i=1}^{N} (F_{it}(P_{it})U_{it} + S_i V_{it}) \quad \textit{(Rs/hr)} \qquad (1b)$$

where,

U_{it} – Unit *i* status at hour *t*

V_{it} – Unit *i* start up/ shut down status at time *t*

F_T – Total operating cost over the schedule horizon (*Rs/hr)*

S_{it} – Startup cost of unit *i* at time *t (Rs)*

3. Constraints

3.1 Load Power balance constraint

The real power generated by thermal and hydro generating units must be sufficient enough to meet the load demand and must satisfy the equation

$$\sum_{i=1}^{N} P_{s,it} + \sum_{j=1}^{M} P_{h,it} = P_{D,i} + P_{L,i} \quad 1 \le t \le T \qquad (2)$$

3.2 Spinning Reserve constraint

Spinning reserve is the total amount of generation available from all units synchronized on the system minus the present load plus the losses being supplied. The reserve is usually expressed as a percentage of forecasted load demand. Spinning reserve is necessary to prevent drop in system frequency and also to meet the loss of most heavily loaded unit in the power system.

$$\sum_{i=1}^{N} P_{\max i} U_{it} \ge (P_{D,i} + R_t) \quad 1 \le t \le T \qquad (3)$$

3.3 Thermal constraints

A thermal unit undergoes gradual temperature changes and this increases the time period required to bring the unit online. This time restriction imposes various constraints on generating unit. Some of the constraints are minimum up/down time constraint and crew constraints.

3.3.1 Minimum Up time

If the units are already running there will be a minimum time before which the units cannot be turned OFF and the constraint is given in (4).

$$T_{on,i} \ge T_{up,i} \qquad (4)$$

3.3.2 Minimum Down time

If the units are already OFF there will be a minimum time before which they cannot be turned ON and the constraint is given in (5).

$$T_{off,i} \ge T_{down,i} \qquad (5)$$

3.4 Must Run units

Some units in the power system are given must run status in order to provide voltage support for the network.

3.5 Unit Capacity limits

The power generated by the thermal unit must lie within the maximum and minimum power capacity of the unit.

$$P_{s,i}^{\min} \le P_{s,i} \le P_{s,i}^{\max} \qquad (6)$$

3.6 Hydro constraints

3.6.1 Hydro Plant generation limits

The power generated by the hydro units must be within the maximum and minimum power capacity of the unit [1].

$$P_{h,i}^{\min} \le P_{h,i} \le P_{h,i}^{\max} \qquad (7)$$

3.6.2 Hydraulic network constraints

Physical limitations on reservoir storage volumes and discharge rates.

$$V_{h,i}^{\min} \le V_{h,i} \le V_{h,i}^{\max} \tag{8}$$

$$Q_{h,i}^{\min} \le Q_{h,i} \le Q_{h,i}^{\max} \tag{9}$$

The initial volume and the final volume that is to be retained at the end of scheduling period.

$$V_{h,it}^{t=0} = V_{h,i}^{begin} \tag{10}$$

$$V_{h,it}^{t=T} = V_{h,i}^{end} \tag{11}$$

The Continuity equation for hydro reservoir network is given in (12).

$$V_h(i,t) = V_h(i,t-1) + I_h(i,t) - S_h(i,t) - Q_h(i,t) - \sum_{m=1}^{Ru} [Q_h(m, t-\Gamma(i,m)) + S_h(m, t-\Gamma(i,m))] \tag{12}$$

3.6.3 Hydro plant unit power generation characteristics

The hydro power generated is related to the reservoir characteristics as well as water discharge rates. Hydro power output is a function of the volume of the reservoir and discharge rate. The equation representing the hydro power generation characteristics is given in (13).

$$P_h(i,t) = C_{1,i} V_h(i,t)^2 + C_{2,i} Q_h(i,t)^2 + C_{3,i}[V_h(i,t) Q_h(i,t)] C_{4,i} V_h(i,t) + C_{5,i} Q_h(i,t) + C_{6,i} \tag{13}$$

4. Tabu Search

4.1 Introduction

Tabu Search utilizes the technique of extended neighborhood search which has been applied to many complicated optimization problems. It is an iterative procedure that searches for a set of feasible solutions in the possible solution space to reach a better solution. Tabu Search provides a means for eliminating the problem of entrapment in local optima by employing a short term memory structure of recently visited solutions. The procedure will shift the direction of the algorithm on the next move during the local optimal condition which may ultimately lead to a better solution. The main two components of Tabu Search algorithm are the Tabu List Restrictions and Aspiration Level of the solution associated with these restrictions. The following sections explain the above mentioned components of TSM [17–19].

4.2 Tabu List Restrictions

The Tabu Search approach for solving UCP is to overcome the problem of local optimality by the strategy of forbidding certain moves that deteriorates the quality of the solution. The purpose of assigning tabu status to certain moves is to prevent cycling which reduces the processor time and also enhances the quality of the solution.

TS introduce the tabu list (TL) to control the change of the attributes. The objective of the tabu list is to avoid short term solution candidates circulating in the solution search space. The tabu list works as a temporary memory that stores attributes during some iterations. The attributes stored in the tabu list are fixed while other attributes are changeable for finding a better solution. Once a new attribute enter the tabu list the older attribute is released from the list. The tabu list length is the parameter that controls the TS performance [17-19].

The TL is designed to ensure elimination of cycles of length equal to the TL size. The TL sizes that provide good solution depend on the size of the problem. For smaller size lists the number of cycles occurring is more. For large size lists the quality of the solution may deteriorate due to the elimination of too many moves. Hence the best size lies in between these extremes. The best size can be found by repeated execution of the tabu search program with different TL sizes [17].

4.3 Aspiration Level

TL stores the solutions that are likely to provide local optima by assigning tabu status to the solutions. But all the solutions in the TL that owns tabu status may not be local optimal solutions. Hence tabu status can be overruled if certain conditions are met expressed in the form of Aspiration Level (AL). If appropriate aspiration criterion is satisfied the tabu status of the solution can be overruled. Hence AL is designed to override tabu status if a move is good enough. Different forms of AL can be used. But the proposed algorithm associates AL with the objective function of the solution obtained during a move. If the tabued move yields a solution with better objective function than the one obtained in the previous move then AL can be used to override the tabu status. AL is used to add flexibility in the tabu search by directing the search towards attractive moves that lead to a better solution [17].

4.4 Termination of the algorithm

The algorithm can be terminated at any time if it satisfies certain conditions. There may be several possible conditions for termination of the algorithm. But the best conditions are selected by the quality of the solution obtained after termination. In this algorithm two possible conditions for termination have been applied. The algorithm will be terminated if the following conditions are satisfied:

- given number of iterations have been performed
- the operating cost repeats successively for certain number of iterations.

4.5 General Tabu Search algorithm

The TSA is applied for solving many combinatorial optimization problems. The iterative algorithm starts with the formation of an initial feasible random solution. Then a move is performed to this initial solution to obtain neighbors to this solution. A move to the neighbor is performed if it is not present in TL or in case of being in TL it passes the AL test. During this search process the best solution is always updated and stored in a variable until the iteration is stopped.

The following notation is used to describe the general TSM algorithm [17] for solving combinatorial optimization problems.

X : the set of feasible solutions for a given problem
x : current solution, $x \in X$
x'' : best solution reached
x' : best solution among a sample of trial solutions
E(x) : objective function of solution x
N(x) : set of neighborhood of $x \in X$ (trial solutions)
S(x) : sample of neighborhood of x; $S(x) \in N(x)$
SS(x): sorted sample in ascending order according to their objective functions, E(x)
TL: tabu list
AL: aspiration level

The steps of general TSM are as follows:

1. Set TL as empty and AL as zero.
2. Set iteration counter K=0. Select an initial solution $x \in X$ and set x'' = x.
3. Generate randomly a set of trial solutions $S(x) \in N(x)$ (neighbor to the current solution x) and sort them in an ascending order, to obtain SS(x). Let x' be the best trial solution in the sorted set SS(x) (the first in the sorted set).
4. If E(x) > E(x'), go to Step 4, else set the best solution x'' = x' and go to Step 4.
5. Perform the tabu test. If x' is not in TL, then accept it as a current solution, set x =x' and update the TL and AL and go to Step 7, else go to Step 5.
6. Perform the AL test. If satisfied, then override the tabu state, set x = x', update the AL and go to Step 7, else go to Step 6.
7. If the end of SS(x) is reached, go to Step 7, otherwise, let x' be the next solution in SS(x) and go to Step 4.
8. Perform the termination test. If the stopping criterion is satisfied then stop, else set K=K+1 and go to step 2.

5. Tabu Search Algorithm (TSA) for UCP

5.1 TSA for solving UCP

The variables used for solving the UCP are the unit status variables U and V which are binary digits either 0 or 1 and the unit output power variable P. The following are the steps of tabu search algorithm for solving the unit commitment problem in hydro-thermal power system.

1. Get the thermal and hydro power system data and load pattern for a day.
2. Calculate the water discharge rates and hence the hydro power output.
3. Calculate the thermal system load P_{dt} by subtracting the hydro power P_{dh} from the total demand P_d.
$$P_{dt} = P_d - P_{dh}$$
4. Initialize all variables (U, V, P) to zero and set the iteration counter K=0.
5. Generate randomly an initial current feasible solution (U_i^0, Vi0).
6. Calculate the total operating cost, F_i^0 for this solution.
7. Set the global best solution equal to the current solution, (U_B, VB) = (U_i^0, Vi0), $F_B = F_i$.
8. Find a set of trial solutions $S(U_i^K,V_i^K)$ that are neighbors to the current solution (U_i^K,V_i^K) with objective values $F^K(S)$ and sort them in an ascending order. Let $SF^K(S)$ be the sorted values. Let (U_b^K,V_b^K) be the best trial solution in the Set, with an objective value F_b.
9. If $F_b \geq F_B$ go to Step 10, else update the global best solution, set $(U_B,V_B) = (U_b^K,V_b^K)$ and go to Step 10.
10. If the trial solution (U_b^K,V_b^K) is NOT in the TL, then update the TL, the AL and the current solution; set

$(U_i^K, V_i^K) = (U_b^K, V_b^K)$, $F_i^K = F_b$ and go to Step 13, else go to Step 11.

11. If the AL test is NOT satisfied go to Step 12 else, override the tabu state, set $(U_i^K, V_i^K) = (U_b^K, V_b^K)$ update the AL and go to Step 13.
12. If the end of the $SF^K(S)$ is reached go to Step 13, otherwise let (U_b^K, V_b^K) be the next solution in the $SF^K(S)$ and go to Step 10.
13. Stop if the termination criterion is satisfied, else set K=K+1 and go to Step 8.

The complete flowchart of TSA for UCP is shown in "Fig. 1".

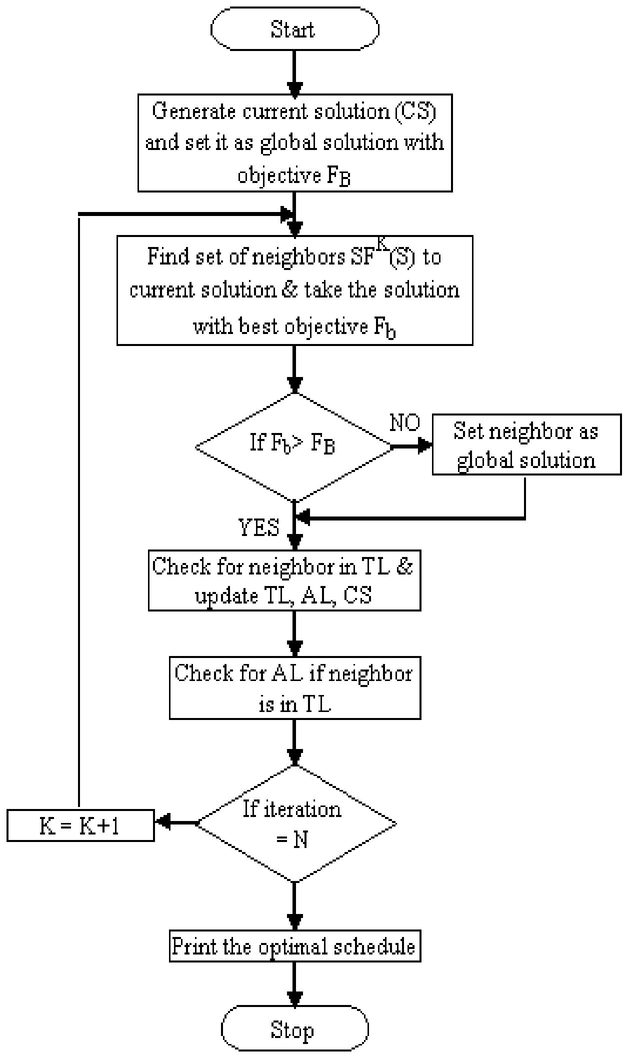

Fig 1: Flowchart for UCP using Tabu Search

5.2 Generation of a Neighbor

Generating a neighbor to the current solution is the important section of the tabu search algorithm [17]. The neighbors created must be feasible to meet the demand and also span as much of the problem solution space as possible. The better is the neighbor created the better will be the final solution. Hence a lot of future work is required in this area to develop a randomly feasible neighbor to the current solution. The additional contribution in this paper is the proposal and implementation of new rules to improve the speed of formation of neighbor and its quality. The new rules implemented to obtain the neighbors to the current solution are described in the following steps. The same rules can be used to create the initial feasible current solution.

1. Consider a unit i and generate randomly a time t, $t \sim UD(1,T)$ and get the status of the unit at t.
2. If the unit i at hour t is ON, then go to Step 3 for switching it OFF around this time t. If the unit i at hour t is OFF then go to Step 4 for switching it ON around this time t.
3. Switching the unit i from ON to OFF:
   a) Move backward and forward in time from the hour t to find the length of the ON period of the unit i. Let the number of ON periods be n.
   b) Note down the time t1 and t2 which are the first and last hours at which the unit is ON.
   c) If the time t obtained randomly is an odd number, then generate an odd number $L \sim UD(1,n)$ and switch OFF all the units starting from t1 till t1+L-1 hour is reached.
4. Switching the unit i from OFF to ON:
   a) Move backward and forward in time from the hour t to find the length of the OFF period of the unit i. Let the number of OFF periods be n.
   b) Note down the time t1 and t2 which are the first and last hours at which the unit is OFF.
   c) If the time t obtained randomly is an odd number, then generate an odd number $L \sim UD(1,n)$ and switch ON all the units starting from t1 till t1+L-1 hour is reached.
   d) If the time t obtained randomly is an even number, then generate an even number $L \sim UD(1,n)$ and switch ON all the units starting from t1 till t1+L-1 hour is reached.
5. Check if the obtained neighbor meets the load demand. If it meets the demand, then the obtained neighbor is feasible, otherwise repeat the above steps to obtain the feasible neighbor to the current solution.

5.3 Formation of Tabu List

The TL is the main component of tabu search technique [17]. It uses short term memory structure to store forbidden moves and prevents the cycling of the forbidden solutions which reduces the processor time. The TL eliminates the cycles of length ‘Z’ where ‘Z’ is the size of the tabu list. The TL can store the ‘Z’ entries of the entire solution matrices. But this requires large amount of memory space and increases the execution time of the algorithm. Hence it is worth proposing different techniques for formation of TL types that utilizes less memory and stores attributes that are most appropriate in representing the solution nature.

In the implementation of different TL types in this paper, a separate TL for each generating unit is created and is called Generating Unit TL (GUTL). Each GUTL has dimensions of Z X L, where L is the recorded attributes length. In this technique, the number of TLs required is equal to the number of generating units. The second technique uses a single TL for the whole solution. Two different techniques to form TL are described in the following section.

5.4 Different types of Tabu List

The two proposed techniques for the formation of TL types are as follows:

5.4.1 Technique 1

This technique uses only one TL for the whole solution. This reduces the space occupied by the TL. Here each entry records the objective function values of the trial solutions generated. Whenever a new objective value is obtained, it is compared with the available values in TL. If the new objective value is found minimum, then its corresponding solution is taken as the current solution and next iteration is performed. If it is not found minimum, then it is stored in TL and the minimum objective value solution in TL is taken as the current solution and next iteration is performed.

5.4.2 Technique 2

In this technique, each GUTL contains one dimensional array of ‘Z’ entries. Each entry records the number of ON periods for the respective unit. This technique represents the solution nature in the most appropriate and easy way. In this technique the assumption is that two solutions with same number of ON periods will have the same operating cost irrespective of their status at different hours in the scheduled horizon.

6. Case Study

An IEEE test system consisting of 4 hydro generating units and 10 thermal generating units has been considered as a case study. A time period of 24 hours is considered and the unit commitment problem is solved for these 10 units power system. The required inputs for solving the UCP are tabulated below. The IEEE thermal test system is shown in Table 1, hydro discharge coefficients, reservoir volumes and discharge limits and inflows to the reservoir are shown in Tables 2, 3 and 4. The daily load pattern considered is shown in Table 5. The operating cost comparison of TS with EP and DP is shown in Tables 6, 7, 8 and 9. The Cost convergence graphs of TS for different iterations are shown in Figures 2 and 3.

Table 1: IEEE thermal test system

Unit	Pmax (MW)	Pmin (MW)	A ($/h)	B ($/MWh)	C ($/MW²h)	Startup Cost ($)	Tup & Tdown (h)
1	455	150	1000	16.19	0.00048	4500	8
2	455	150	970	17.26	0.00031	5000	8
3	130	20	700	16.6	0.002	550	5
4	130	20	680	16.5	0.00211	560	5
5	162	25	450	19.7	0.00398	900	6
6	80	20	370	22.26	0.00712	170	3
7	85	25	480	27.74	0.00079	260	3
8	55	10	660	25.92	0.00413	30	1
9	55	10	665	27.27	0.00222	30	1
10	55	10	670	27.79	0.00173	30	1

Table 2: Hydro discharge coefficients

UNIT	C_1	C_2	C_3	C_4	C_5	C_6
1	-0.0042	-0.42	0.03	0.9	10	50
2	-0.004	-0.3	0.015	1.14	9.5	70
3	-0.0016	-0.125	0.014	0.55	5.5	40
4	-0.003	-0.31	0.027	1.14	14	90

Table 3: Reservoir volume & discharge limits (x 10^4 m^3)

Unit	Vmin	Vmax	Vini	Vend	Qmin	Qmax	Pmin	Pmax
1	0	200	100	100	0	30	0	500
2	0	200	100	100	0	30	0	500
3	0	350	150	150	0	40	0	500
4	0	350	150	150	0	40	0	500

Table4: Inflows to the reservoir (x 10^4 m^3)

UNIT	1	2	3	4	5	6	7	8
1	12	12	11.8	11.7	11.7	11.6	11.5	11.4
2	6	6	6.5	6.7	6.8	6.9	7	7.2
3	3	4	5	6	7	8	8.8	8.9
4	3	2	2	0	0	0	0	0

Table 5: Load pattern for 24 hours

PERIOD (h)	LOAD (MW)	PERIOD (h)	LOAD (MW)
1	1400	13	2075
2	1450	14	2000
3	1350	15	1900
4	1650	16	1750
5	1700	17	1800
6	2000	18	1900
7	1850	19	1950
8	1900	20	2100
9	2000	21	2050
10	1400	22	1800
11	2100	23	1600
12	2150	24	1500

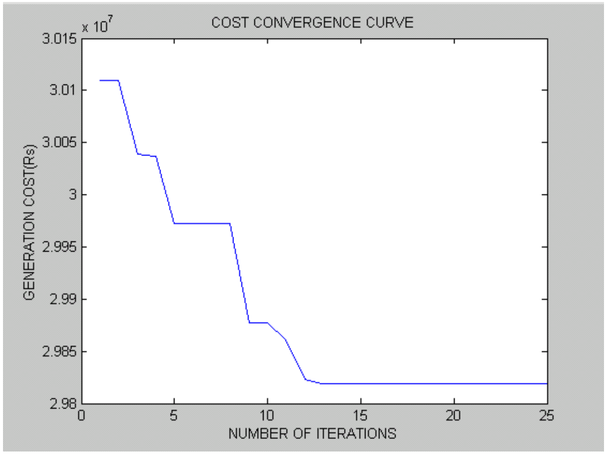

Fig 2: Cost convergence characteristics for 25 iterations with TL size=10

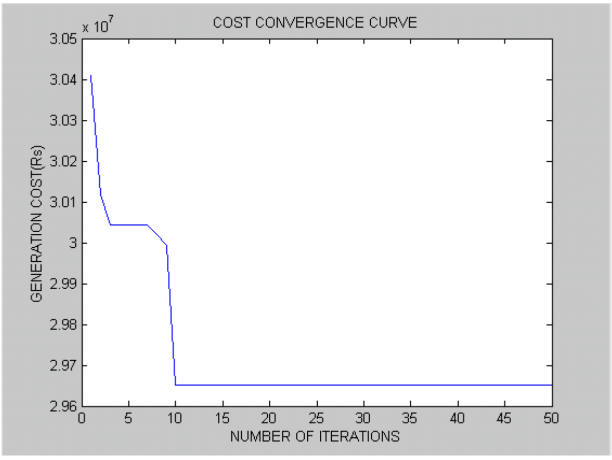

Fig 3: Cost convergence characteristics for 50 iterations with TL size=10

Table 6: Production cost for different techniques

Technique	Iterations	Production Cost (Rs)	Production Cost (p.u.)	Convergence time (sec)
DP	-	3,27,74,013	1.0	3.9
EP	25	3,06,56,586	0.9354	73.65
EP	50	3,03,03,012	0.9246	144.51
TS	25	2,98,19,243	0.9098	18.07
TS	50	2,96,51,741	0.9047	35.48

Table 7: Comparison of costs for different TL types

Technique No.	1	2
Cost (Rs)	2,96,51,741	2,98,84,529

Table 8: Comparison of costs for different TL size

TL size	5	10	15	20
Cost (Rs)	3,00,92,462	2,96,51,741	2,99,90,843	3,01,71,755

Table 9: Cost for different trial solutions formed

Number of trial solutions formed	5	10	14	20
Cost (Rs)	3,00,54,542	3,00,24,486	2,96,51,741	3,02,13,153

UCP is solved using the tabu search method. The results obtained during the execution of the program clearly provide the following observations. The better final solution of UCP is mainly influenced by the initial current feasible solution. If the current solution provides a better objective function then the final solution obtained reaches the global optimum solution with probability very close to one. The time of execution taken by TSA to solve UCP is equal to 25 % of the time of execution taken by EP. The size of the TL also influences the quality of the final solution obtained. The better solutions are obtained for the tabu list size of 10. The percentage of escape from the local optima for the proposed algorithm is almost reaching 70%. From the two types of TL proposed, better solutions are obtained in the case of Technique 1. The size of the TL does not affect the time of execution of the program but it is limited by the deterioration in the quality of the solution obtained.

7. Conclusions

In this paper a new hybrid algorithm for solving the unit commitment problem in a hydro-thermal power system is proposed. The TS is characterized by its ability to escape from the local optima by employing short term memory structure. The TS also has a strategy called AL which directs the search towards attractive moves leading to a better ultimate solution. Different techniques for constructing tabu list have been proposed and tested which provided good solutions. The effectiveness of the algorithm is proved by considering an IEEE thermal and hydro test system. The results obtained from the proposed algorithm are better than the results obtained from the other methods tried. The Tabu Search algorithm can be used as a powerful tool for solving many combinatorial optimization problems. Even better solutions can be obtained by employing sophisticated procedures in the formation of trial solution and tabu list. Thus the ability of tabu search method to escape local optima with reduced computation time proves the strength of the algorithm.

8. Nomenclature

E_c : Energy of the current configuration
E_{Config} : Energy of a given configuration
E_t : Energy of the trail configuration
$F_{it}(P_{it})$: Production cost of unit i at a time t (Rs/hr.)
F_T : Total operating cost over the scheduled horizon (Rs/Hr)
K : Constant
N : Number of available generating units
P_{Config} : Probability of a given configuration
PD_t : System peak demand at hour t (MW)
P_{it} : Output power from unit i at time t (MW)
P_{maxi} : Maximum generation limit of unit i (MW)
P_{mini} : Unit i minimum generation limit (MW)
R_t : Spinning reserve at time t (MW).
S_{it} : Start up cost of unit i at hour t (Rs).
S_{oi} : Unit i cold start – up cost (Rs).
T : Scheduled time horizon (24 hrs)
$Tdown_i$: Unit i minimum down time (Hr)
$Toff_i$: Duration for which unit i is continuously OFF (Hr)
Ton_i : Duration for which unit i is continuously ON (Hr)
$Tshut_i$: Instant of shut down of a unit i (Hr)
$Tstart_i$: Instant of start up of a unit i (Hr)
Tup_i : Unit i minimum up time (Hr)
U (0,1) : Uniform distribution with parameters 0&1
U_{it} : Unit i status at hour t = 1 (if unit is ON) = 0 (if unit is OFF)
UD (a,b): Discrete uniform distribution with parameters a and b.
V_{it} : Unit i start up /shut down status at hour t = 1if the unit is started at hour t and 0 otherwise.
F : Composite cost function
F_i : Fuel cost of i^{th} thermal unit in Rs/hr
$P_s(i,t)$: Generation of i^{th} thermal unit at time t in MW
$P_h(i,t)$: Generation of i^{th} hydro unit a time t in MW
$V_h(i,t)$: Storage volume of i^{th} reservoir at time t in m^3
$Q_h(i,t)$: Water discharge rate of i^{th} reservoir at time t in m^3
$P_D(t)$: Power demand at time t in MW
$P_L(t)$:Total Transmission line losses at time t in MW
$S_h(i,t)$: Spillage of i^{th} reservoir at time t in m^3
$I_h(i,t)$: Inflow rate of i^{th} reservoir at time t in m^3
$H_i(t)$: Net head of i^{th} reservoir at time t in m^3
α,β,γ : Thermal generation cost coefficients
$C_{i,1}$ to $C_{i,6}$: Hydro power generation coefficients
$\tau_{i,m}$: Water transport delay from reservoir σ to i
R_u : Set of upstream units directly above i^{th} hydro unit
R_h / R_s : Set of Hydro/Thermal plants in the system
i,m : Reservoir index, index of reservoir upstream of the i^{th} reservoir
t,T : Time index, scheduling period
V,i^{begin} : Initial storage volume of i^{th} reservoir in m^3
V,i^{end} : Final storage volume of i^{th} reservoir in m^3
P_i : Output generation for unit i in MW
P_L : Total current system load in MW
PT_L : Total system transmission losses in MW
OBJ : Objective cost function
F_i : Cost function for unit i

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