A Computational Tool for Dispatching Units in Pool-Based Electricity Markets

M. Oloomi-Buygi, Ali Karimpour and Naser Pariz

Abstract—**In this paper a new approach for solving mixed-integer nonlinear programming problems is presented. The approach is named probabilistic search. The main idea is to search the feasible solution area probabilistically instead of randomly. The presented approach is used to determine the dispatch value of each generator in a pool-based electricity market. In this approach the ON and OFF units are determined using the probabilistic search and the generation value of each unit is determined using the linear programming. A software was developed based on the proposed approach for unit commitment. The software is used in the Iranian electricity power pool now.**

Index Terms— **Unit commitment, Mixed-Integer nonlinear programming, Probabilistic search, Genetic Algorithms, Electricity market**

I. Introduction

In the last years, the power industry is undergoing massive changes due to restructuring. Different structures are used for electricity markets around the world. New issues both in operation [1-2] and planning [3-4] have been emerged in the new environment. Hence, new tools are required to dispatch units in new environments. The presented approaches for dispatching units can be classified into four groups [5]–[12]: a) priority list [5]; branch-and-bound [6-7]; Lagrangian relaxation [8]; and Meta-heuristic methods [9]–[12].

Priority list methods commit units in ascending order of their full-load cost. Therefore to meet the demand first the most economic unit is committed and the worst economic unit is committed after committing all other units, if it is needed. Priority list methods are fast scheduling methods but their schedule is not optimal and has relatively high operation cost. In branch-and-bound methods calculation time may increase enormously in large scale problems. Lagrangian relaxation methods concentrate on finding an appropriate coordination technique to generate feasible primal solutions, while minimizing the duality gap. The main drawback of Lagrangian relaxation methods is difficulty in generating feasible solutions. The meta-heuristic methods are iterative search techniques that can search throughout feasible area to find the global optimal solution. These methods can take into account various constraints. Genetic algorithm is a meta-heuristic method that frequently applied to the unit commitment problem. Genetic algorithm searches the feasible area randomly using crossover and mutation operator. Therefore it needs a long time to find the optimal solution. In order to find the optimal solution faster, search in the feasible area must be directed. In this paper a probabilistic search method is presented to increase the speed of finding optimal solution. The presented method is used for computing the dispatched value of each unit in a pool-based electricity market.

The paper is organized as follows. In section II an approach for solving mixed-integer nonlinear programming problems, which is named probabilistic search, is presented. In section III the presented approach is used for power system unit commitment. The proposed unit commitment approach is applied to Iranian electricity power pool in section IV. Conclusion in section VI closes the paper.

II. Probabilistic Search

Consider a mixed-integer programming problem and suppose we are going to solve it using Genetic Algorithm. Assume S is a member of initial population. Each cell of S is 0 or 1. Genetic Algorithm searches the feasible solution area randomly by crossover and mutation operators. Normally the feasible solution area is very large and it takes a long time to find the optimal solution by random search. In some programming problems it is possible to determine the ON/OFF probability density function (pdf) for each cell of S. In the other word it is possible to determine the probability of being 1 for each cell of S. Let us name it ON probability. Fig 1 shows a typical member with ON/OFF pdf of each cell. The first column of each pdf shows OFF probability and the second one shows the ON probability. In some problems it is possible to determine the joint probability density function for the cells of S. Fig 2 shows a

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typical two-cell member with their joint ON/OFF pdf. In both abovementioned problems, in order to find the optimal solution faster, the feasible solution area is searched probabilistically instead of randomly, i.e. the parts of feasible solution area that are more probable to contain the optimal solution are searched more carefully than the other parts. The probabilistic search algorithm is as follows:

a) Member generation: in the case that ON/OFF pdf of each cell is available, a standard uniform pdf is assigned to each cell of member S. A number is selected from the standard uniform pdf of each cell randomly. The selected number is compared with the related ON probability. If the selected number is less than or equal to the related ON probability the value of this cell is 1 else it is 0. In the case that joint ON/OFF pdf of cells is available, first ON/OFF pdf of each cell is computed and then the above-mentioned algorithm is used to generate a new member. In this case the following approach also can be used to generate new member. Suppose n_c is number of cells of member S. An n_c dimensional standard uniform joint pdf is assigned to the member. A point is selected from the assigned standard uniform joint pdf randomly. Based on the location of selected point in n_c dimensional space, we can determine which cell is one (ON) and each cell is zero (OFF). For example consider a two-cell member, suppose the ON probability of cells are p_1 and p_2 respectively. Assume the coordination of selected point from standard uniform joint pdf is (x,y). then:

$$\text{If } x \le p_1 \ \& \ y \le p_2 \text{ then } C_1 = 1 \ \& \ C_2 = 1$$
$$\text{If } x \le p_1 \ \& \ y \ge p_2 \text{ then } C_1 = 1 \ \& \ C_2 = 0$$
$$\text{If } x \ge p_1 \ \& \ y \le p_2 \text{ then } C_1 = 0 \ \& \ C_2 = 1$$
$$\text{If } x \ge p_1 \ \& \ y \ge p_2 \text{ then } C_1 = 0 \ \& \ C_2 = 0$$

b) Member selection: after generating a new member its fitness function is computed. The fitness function of new member is compared with the fitness function of previous member, and the best one is saved.

Above procedure is repeated until stop criteria is satisfied. Stop criteria can be number of iteration or rate of improving fitness function. Note that the members that are created using the above procedure have more chance to be the optimal member than the members that are created randomly using crossover and mutation operators.

1	0	...	0	1

Fig. 1 – A typical member with pdf of each cell

0	1

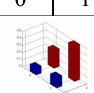

Fig. 2 – A typical two-cell member with joint pdf of cells

III. Unit Commitment Using Probabilistic Search

Consider a power pool that contains some generation units. Suppose the units offer their bids for 24 hours of the next day. The power pool must schedule the units for the next day by minimizing the total payments to the generation units subject to technical constraints of units and transmission network. It is assumed that the load has been forecasted for the 24 hours of the next day. The proposed algorithm for unit commitment using probabilistic search is as follows.

1. Initialize iteration counter: l=1.
2. Construct a $n_g \times n_t$ array and name it member S^l. where n_g is number of the generation units and n_t is the number of hours of programming period, normally 24 hours. Row i of S^l indicates unit i and column h of S^l indicates hour h. Fig. 3 shows a typical member.

	1	2	3	4	...	21	22	23	24
1									
2									
⋮									
n_g-1									
n_g									

Fig. 3 – A typical member for unit commitment

3. Apply must run/off constraints. The units that must be ON/OFF at hour h are called nonflexible units of hour h. Number 2/-2 is assigned to the cell ih, if unit i is a nonflexible ON/OFF unit at hour h. The units that can be ON or OFF at hour h are named flexible units of hour h. For example suppose unit 1 is must run at hours 2 and 3 and unit 2 is must off at hours 23 and 24. Member of Fig 3 after applying must run/off constraints is shown in Fig 4.

	1	2	3	4	...	21	22	23	24
1		2	2						
2								-2	-2
⋮									
n_g-1									
n_g									

Fig. 4 – Member S^l after applying must run/off constraints

4. Create a priority list for each hour based on average bids of each unit. A typical priority list is shown in Fig 5.

1	2	3	4	...	21	22	23	24
2	3	n_g	5		3	5	4	5
5	1	4	2		n_g	1	2	1
⋮								
12	2	1	6		5	n_g	7	4
1	4	7	4		6	7	6	6

Fig. 5 – A typical priority list

Column 1 of the priority list of Fig 5 says at hour 1 generator 2 has the lowest bid. After generator 2, generator 5 has the lowest bid. Generator 1 has the highest bid.

5. Assign a standard uniform pdf to each cell of S^l.
6. Initialize hour counter: h=1.

7. Apply min up/down times constraints. Compare the long time that each unit has been ON/OFF till end of hour h-1 with its min up/down times and determine the nonflexible units of future hours. For example suppose min up time of generator 2 is 4 hours. Suppose generator 2 has been ON for two hours untill the beginning of hour 1. Then it must be ON at least in next two hours. Member of Fig 4 after applying min up time constraint of generator 2 is shown in Fig 6.

	1	2	3	4	…	21	22	23	24
1		2	2						
2	2	2						-2	-2
⋮									
n_g-1									
n_g									

Fig. 6–Member S^l after applying min up/down time constraint of Gen 2

8. Determine dispatch probability of each unit. Suppose the units are dispatched according to priority list to meet the demand of hour h. The first unit of priority list has a high chance to be dispatched hence 0.9 is assigned to dispatch probability of this unit. The last unit of priority list has a very low chance to be dispatched; only in constrained cases will be dispatched. Hence 0.1 is assigned to dispatch probability of this unit. Marginal generator has equal chance for dispatching and not dispatching. Hence 0.5 is assigned to its dispatch probability. The next generator after marginal generator in the priority list has approximately equal chance for dispatching and not dispatching. Hence 0.5 is assigned to dispatch probability of this unit too. A dispatch probability is assigned to each other generator according to its place in the priority list by linear interpolating. Assigned dispatch probabilities based on the priority list of Fig 5 are shown in Fig 7. According to priority list of Fig 5, at hour 1 generator 2 has the lowest bid and generator 1 has the highest bid therefore dispatch probability of generators 2 and 1 are equal to 0.9 and 0.1 respectively. Dispatch probability of marginal generator and the next one in the priority list is equal to 0.5. Dispatch probabilities of other generators are determined by linear interpolating.

	1	2	3	4	…	21	22	23	24
1	0.1	0.8	0.2	0.7		0.6	0.8	0.7	0.9
2	0.9	0.2	0.7	0.8		0.4	0.6	0.8	0.6
⋮									
n_g-1	0.8	0.6	0.5	0.4		0.7	0.7	0.5	0.7
n_g	0.3	0.7	0.9	0.6		0.8	0.2	0.3	0.3

Fig. 7 – Dispatch probabilities

9. Determine the ON and OFF units at hour h. A random number is selected from the standard uniform pdf of each flexible units of hour h and is compared with its dispatch probability. If the selected number is less than or equal to the corresponded dispatch probability, the related unit must be ON and 1 is assigned to its related cell. Otherwise it must be OFF at this hour and –1 is assigned to its related cell. Suppose the selected random numbers for flexible units 1, n_g-1, and n_g at hour 1 are 0.5, 0.7, and 0.2 respectively. Comparing selected numbers with their related dispatch probability determines ON and OFF units of hour 1. Fig 8 shows the member of Fig 6 after determining ON and OFF units at hour 1. Numbers 2 & 1 / -2 & -1 indicate that the related unit is ON / OFF.

	1	2	3	4	…	21	22	23	24
1	0	2	2						
2	2	2						-2	-2
⋮									
n_g-1	1								
n_g	1								

Fig. 8 – Member S^l after determining ON and OFF units at hour 1

10. Check the sufficiency of ON units to meet the demand and spinning reserve of hour h. If the max generation of ON units of hour h is less than the sum of loads and required spinning reserve of hour h, increase the dispatch probability of OFF flexible units of hour h and run step 9 for OFF flexible generators till ON units can meet the load and spinning reserve of hour h. If the max generation of ON units is greater than 1.2 times of the sum of loads and required spinning reserve, decrease dispatch probability of ON flexible units of hour h and run step 9 for ON flexible units till max generation of ON units is less than 1.2 times of the sum of loads and required spinning reserve of hour h.
11. Check the inter area tie-line constraints. Compute the min power that may be transmit from each inter area tie-line by the max and min generation of each area and compare it with its limit. If some limits are violated. Determine the set of areas that must decrease their generation to alleviate congestion, call it set S_D. Determine the set of areas that must increase their generation to alleviate congestion, call it set S_I. Increase/decrease the dispatch probability of units of set S_I/S_D and run step 9 for flexible OFF/ON units of set S_I/S_D till inter area tie-line constraints are satisfied.
Each congested tie-line has a source and sink area. Suppose only one tie-line is congested. S_D includes its source area and the areas which deliver power to its source area. S_I includes its sink area and the areas which receive power from its sink area. Now assume more than one tie-line is congested. Suppose S_D^j / S_I^j is the set of areas that must decrease / increase their generation to alleviate the

congestion of line j. S_D and S_I are computed as follows:

$$S_D = \bigcup_j S_D^j , \qquad S_I = \bigcup_j S_I^j$$

In strongly meshed networks S_D and S_I may have intersection. Common members must be omitted from both sets.

12. Increase h (h=h+1). Has the procedure been committed for all hours of the program? If No go to step 7, else go to 13.
13. Determine the optimal generation power of each ON generator at each hour. In this step a 24-hour linear optimization is committed to determine the optimal generation power of each ON generator at each hour. The objective function is the sum of total payment to the generation units and load reduction cost. The constraints are min and max generation limits, increase and decrease generation rate limits, max and min energy limits, and inter area tie-lines limits.
14. Compare the objective function value of members S^l and S^{l-1}, if the objective function value of S^l is smaller than the objective function value of S^{l-1}, save S^l.
15. Increase l (l=l+1). Is the stop criteria are satisfied? If No go to step 2, else stop.

IV. Application

In this section the proposed approach is applied to Iranian electricity market which is a single sided pay-as-bid electricity market. Iranian electricity market has about 370 units. All units submit their bids in ten steps for 24 hours of the next day. Each area forecasts its loads for 24 hours of the next day and submits to power pool. The power pool buys electricity from the units by minimizing total cost considering technical constraints of units and transmission network including min up/down times, min/max generation limits, increase/decrease generation rate limits, max/min energy limits, and inter area tie-lines limits. Unit commitment in Iranian electricity market can be formulated as follows:

$$\min \sum_{h=1}^{24}\sum_{i=1}^{N}\sum_{s=1}^{10} \rho_i^{hs} p_i^{hs}$$

S.t.

$$1) \sum_{i=1}^{N}\sum_{s=1}^{10} p_i^{hs} = D^h \qquad h = 1,...,24$$

$$2)\ p_{mn}^h = \sum_{i\in\mathcal{N}_m}^{N}\sum_{s=1}^{10} p_i^{hs} - D_m^h$$

$$p_{mn}^{min} \le p_{mn}^h \le p_{mn}^{max} \qquad h = 1,...,24, \quad m = 1,...,M$$

$$3)\ p_i^{min\,s} \le p_i^{hs} \le p_i^{max\,s} \qquad s = 1,...,10,\ i = 1,...,N,\ h = 1,...,24$$

$$4)\ R_i^h = \sum_{s=1}^{10} p_i^{hs} - \sum_{s=1}^{10} p_i^{(h-1)s}$$

$$\text{if } R_i^h \ge 0 \text{ then } R_i^h \le R_i^{inc}$$

$$\text{if } R_i^h \le 0 \text{ then } -R_i^h \le R_i^{dec}$$

$$i = 1,...,N,\ h = 1,...,24$$

$$5) \sum_{h=1}^{24}\sum_{s=1}^{10} p_i^{hs} \le E_i^{max} \quad i \in \mathcal{N}_{max}$$

$$6) \sum_{h=1}^{24}\sum_{s=1}^{10} p_i^{hs} \ge E_i^{min} \quad i \in \mathcal{N}_{min}$$

$$7)\ \text{If } 0 \le T_{i-1} \le T_i^{on} \text{ then } \sum_{s=1}^{10} p_i^{hs} \ge 0$$

$$\text{If } 0 \le -T_{i-1} \le T_i^{off} \text{ then } \sum_{s=1}^{10} p_i^{hs} = 0$$

$$\text{If } \sum_{s=1}^{10} p_i^{hs} = 0 \ \&\ \sum_{s=1}^{10} p_i^{(h-1)s} \ge 0 \text{ then } T_i = -1$$

$$\text{If } \sum_{s=1}^{10} p_i^{hs} \ge 0 \ \&\ \sum_{s=1}^{10} p_i^{(h-1)s} = 0 \text{ then } T_i = +1$$

$$\text{If } \sum_{s=1}^{10} p_i^{hs} \ge 0 \ \&\ \sum_{s=1}^{10} p_i^{(h-1)s} \ge 0 \text{ then } T_i = T_i + 1$$

$$\text{If } \sum_{s=1}^{10} p_i^{hs} = 0 \ \&\ \sum_{s=1}^{10} p_i^{(h-1)s} = 0 \text{ then } T_i = T_i - 1$$

$$i = 1,...,N,\ h = 1,...,24$$

$$8)\ \text{If } p_i^{hs} = 0 \text{ then } p_i^{ht} = 0 \text{ for } t > s$$

where the used symbols are defined as follows:

N	number of generators
M	number of control areas
$\mathcal{N}_m$	set of units which located in area m
$\mathcal{N}_{max}$	set of units which have max energy constraint
$\mathcal{N}_{min}$	set of units which have min energy constraint
p_i^{hs}	power of step s of unit i at hour h (MW)
p_i^{min}	min power of of unit i (MW)
$p_i^{max\,s}$	max power of unit i (MW)
ρ_i^{hs}	bid of step s of unit i at hour h (Rial/MWh)
D_m^h	forecasted load of area m at hour h (MW)
D^h	forecasted load of the network at hour h (MW)
p_{mn}^h	transmission power from area m to the network at hour h (MW)
p_{mn}^{min}	min allowable of p_{mn} (MW)
p_{mn}^{max}	max allowable of p_{mn} (MW)
R_i^h	generation rate of unit i from hour h-1 to h (MW/h)
R_i^{inc}	max increase rate of unit i (MW/h)
R_i^{dec}	max decrease rate of unit i (MW/h)
T_i	up / down time of unit i (h)

T_i^{on} min up time of unit i (h)

T_i^{off} min down time of unit i (h)

E_i^{min} min energy of unit i at market day (MWh)

E_i^{max} max energy of unit i at market day (MWh)

Constraints 1-8 are load supplying, inter area, min / max generation, increase / decrease generation rate, max energy, min energy, min up / down time, and step relation constraints respectively. To model different steps of a unit, each step is considered as a single generator and constraint 8 is added to related power of different steps.

A Software, which is named PSUC, was developed using the proposed algorithm for the unit commitment of generators at Iranian electricity market. In this Software ON and OFF units are determined using the probabilistic search and the generation value of each unit is determined using the linear programming. It takes about 20 minutes to find the optimal solution using a 266 MHz computer. The software was tested for two mouths. It passed the tests successfully. It has been used in Iranian electricity market for one year.

V. Conclusion

An approach for solving mixed-integer nonlinear programming problems is presented. In this approach in order to reduce the optimization time the feasible solution area is searched probabilistically instead of randomly. The presented approach is used for unit commitment. A software was developed based on the proposed approach and is used in the Iranian electricity power pool. The software determines the optimal solution for the unit commitment of 370 generators, which have ten step bids, in about 20 minutes using a 266 MHz computer.

VI. Acknowledgement

The authors appreciate Moham Shargh Engineering Company due its support for developing the software PSUC.

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