Abstract: In this paper, a new hybrid procedure by a Dynamic Programming (DP) and game theory (GT) is introduced to determine Generation Expansion Planning (GEP) in Pool market. Unlike traditional policy, GEP problem in competitive framework is complicated because of conflicting among Generation Companies (GENCOs). Each GENCO decides to invest in such a way that obtains as much profit as possible. In this paper, a new algorithm is introduced for solution of GEP problem in the pool market. The introduced algorithm is divided in two programming levels: master and slave. In the master level, GT of Cournot model is proposed to evaluate the contrast of GENCOs by regulatory body. In the slave level, in the slave level, a DP method is used to find the best solution of each GENCO for decision making of investment. The satisfactory results show the consistency with expectation.

Keywords: GEP, DP, pool market, Game Theory, MCP

1 Introduction

GEP is an important issue in power system studies, while GEP is to determine what generating unit should be constructed and when generating units should come on line over a long term planning horizon [1]. The approaches of GEP in the restructured power system, is dependent on models of power market (i.e. pool market or bilateral market) [2-6]. In the other words, the objective function of GEP problem in the different market of countries, with consideration of power market models and also purposes of system operator and planning, is different. Generally, GEP in competitive framework, unlike traditional policy, can be analyzed in two levels: national level and regional level [7]. In the national level, the central entity such as Independent System Operator (ISO) or regulatory body is responsible for power system stabilization and manage the GENCOs to consider constrains of power system such as reserve margin, fuel mix and etc. In the regional level, the GENCOs individually seek maximum profit considering its own financial and technical constrains. In this paper, the national and regional level are named as master and slave level, respectively.

In the pool competitive framework, GENCOs with various types of generation units compete with each other to maximize their own profit. In this framework, each GENCO bids its price in market based on its marginal cost and the regulatory body clears the market and determines market clearing price (MCP). MCP and other necessary information for planning are transmitted to each GENCO of system, separately [2,8-9].

The game theory with 3-players, that each of them has only one type of generation unit, is used for GEP in a competitive electric power industry and solved by using Genetic Algorithm (GA) in [2]. This method determines the GEP problem for single time horizon and its output does not includes any information of the years before the time horizon. In this method, for a GEP with a 5-year time horizon for example, the presented method estimates the developed capacity exactly for 5 year later and does not includes any information of 1 or 2 years before the deadline. In other words, for 5-year time horizon GEP, the proposed method cannot estimate the condition of the system for the third or forth years of time interval. Furthermore, this work estimates the developed capacity of the available plants and does not suggest a new generating unit construction. As a contribution of our work, the mentioned problem of GEP is solved in the proposed method. In [8], a framework for GEP in a competitive environment is presented and proposed GA as a useful technique in solving GEP optimization problem. In [9], a competitive GEP problem with 5-player, that each with only one type of generation unit, is presented. In this work, at first, each GENCO individually optimized its own objective function in an iterative manner. After that, the GEP problem is solved to determine the developed capacity of system for a given single-time horizon. The presented work however, use a simple objective function and also MCP considered as a constant term in market. Another contribution of the
proposed method is determining of MCP in pool market by using Bertrand model.

GEP problem for Primal competitive model is discussed in [4-6]. In this model, several Independent Power Producers (IPPs) sell their power only to the utility. A Multi Attribute Decision Making (MADM) is proposed to solve GEP problem in competitive framework for price taker firms [3] and price maker firms [10]. In [7], GEP problem is studied in china only in national level, using intelligent engineering.

In this paper, the GEP in pool market for a multi-time period (time horizon) in regional level is solved by DP method. This method not only can restrict searching space but also can consider complete enumeration in searching space. This section of algorithm is named slave programming. In this section each GENCO make decision of investment for maximization profit. In national level, With the entrance of strategic conflict and gaming, GENCOs encounter more risk and thereby, each GENCO intends to obtain more profit. In this policy in fact, the decision-making of each GENCO affects the other firm’s profit and decision making. This paper used a GT model based on Cournot model to solve the conflict among GENCOs in the master level of algorithm. Contribution of this paper can be summarized as follows:

a) Introducing a hybrid GT/DP algorithm. The new algorithm is applicable to GENCOs with multi-type generating units in pool market.

b) Determining the type of power plant to be installed in addition to the capacity of power plan in time horizon.

c) Presenting a multi-time horizon GEP in a pool market. For a given time horizon, the introduced method not only determine the required power plant installation of the interest horizon, but it also can successfully estimate the required power plant installation of any arbitrary year before the horizon in a correlating manner.

In Section II the DP method is described to solve GEP problem in slave level. The mathematical formulation of objective function and constrains of GEP problem in Pool market is taken Section III. In section IV, a hybrid DP/GT algorithm for solution of GEP in Pool market is presented. Section V includes numerical results. Finally, conclusions are taken in the last section.

2 DP corresponding to GEP

As for as we know, the generation expansion planning is essentially an optimization problem. From the optimization method, GENCOs can get a both economical and feasible investment project. DP is a kind of method for optimization. DP is used because of several reasons. DP takes time as the horizon and calculates the maximum profit path in the intervals. On the other hand, when a GENCO were making an investment decision, it was usually accompanied with many complicated constrains. These constraints are difficult to solve by nonlinear Programming or other methods but can be easily incorporated and solved by the DP method. Also, the number of generating units for investing is integer and DP is a suitable one to solve this kind of problems by integers [11]. Suppose that there are N feasible states when we arrive at interval K, each state has N paths from interval K -1 to interval K. In each interval, for all states, a path that obtains maximum profit should be saved and this operation should be done until final period (interval). Therefore, in the final interval, a path that results maximum profit obtains. The number of combination in each interval equal to . For K interval, number of possible combination equal to . In consideration of many combinations in DP, we can restrict number of states (N) and paths (X) in each interval. Therefore, calculations will be reduced very much. If N, X is greater, final result will be more near to optimum and speed running of program will be lower. The DP method with restricted searching space is presented in Fig.1.

3 Formulation of GEP in Pool market

In a pool market, the decision-making of each GENCO with objective of profit maximization depends on capacity investment based on its forecasted demand, market clearing price, business strategies, and etc. All GENCOs should make decision on future capacity investments without exchanging information with other GENCOs. However, general information such as MCP, fuel mix ratio, reserve margin, and etc. are transmitted by the regulatory body to each GENCO, separately. In
this paper, a new mathematical framework for GEP problem based on pool market model is proposed with the intention that it becomes match with DP technique. Accordingly, objective function for the $i^{th}$ GENCO can be written as follows:

$$
\max B_{N,i}^k = \{R_{N,i}^k(P_{N,i}^k) - [C_{N,i}^k(q_{N,i}^k) + F_{N,i}^k(p_{N,i}^k) - S_{N,i}^k(q_{N,i}^k)]\} + B_{N,i}^{k-1}
$$

(1)

$$
R_{N,i}^k = MCP^k - \alpha \sum_{i=1}^{G} P_{N,i}^k
$$

(2)

Where

- $i = 1, 2, ..., G$
- $B_{N,i}^k$: Profit ($) from Pool market in state N, interval (year) K for GENCO-i
- $R_{N,i}^k$: Revenue ($) from Pool market in state N, interval (year) K for GENCO-i
- $C_{N,i}^k$: Investment cost ($) for construction of new generation unit in state N, interval (year) K for GENCO-i
- $F_{N,i}^k$: Fuel and O&M costs for existing unit and adding unit ($) in state N, interval (year) K for GENCO-i
- $S_{N,i}^k$: Salvage value of investment costs ($) in state N interval (year) K for GENCO-i
- $P_{N,i}^k$: Existing and new adding capacity (Mw) in state N interval (year) K for GENCO-i
- $q_{N,i}^k$: New adding capacity (Mw) in state N interval (year) K for GENCO-i
- $MCP^k$: Market clearing price ($) in interval (year) K
- $\alpha$: Demand factor illustrative of price elasticity in Pool market

The constraints of the solution model include state constraints and path constraints. Some of constraints decrease number of states and some of constraints increase number of paths from state N in interval K to state M in interval K+1. Constrains of objective function are given as follows:

- **Limitation of construction**
  The number of the various types of generation units in each interval (year) is limited due to time of construction of generation unit. This constraint is a path and regional constraint and is expressed follow as:

$$
U_{N,M}^{K,j} \leq X^{K,j}
$$

(3)

Where

- $U_{N,M}^{K,j}$: Path starting from the N-th state in interval K-to the M-th state in interval K and its dimension is the number of different types of units.

$U_{N,M}^{K,j}$ : Number of new generation units of j-type from path $U_{N,M}^K$

$X_{N,M}^{K,j}$: Standard of maximum number construction of new generation unit of j-type in interval K

- **Fuel mix constraint**
  Power system includes various types of power plants. In order to keep the security of system at an acceptable level, the total capacity of peak type generating unit such as gas turbine and oil, must be more than a certain percent of the total capacity of base type units (e.g. nuclear, coal). This constraint is a path constraint. It can be formulated as follow:

$$
\sum_{j=1}^{G} \beta \cdot Ub_{N,i}^k \cdot q_{N,i}^k \leq \sum_{j=1}^{G} Up_{N,i}^k \cdot q_{N,i}^k
$$

(4)

Where

- $\beta$: Fuel mix ratio

$Ub_{N,i}^k$: Number of new base type generating unit in state N, interval (year) K for GENCO-i

$q_{N,i}^k$: Capacity of new base type generating unit (Mw) in state N, interval (year) K for GENCO-i

- **Limitation of capacity constraint**
  This constraint is a state constraint. It depends on financial limit of each GENCO and can control market power in Pool market. This is a regional constraint and can be expressed as follow:

$$
q_{\text{max}} \leq q_{N,i}^k \leq q_{\text{min}}
$$

(5)

Where

- $q_{\text{max}}$: Maximum capacity
- $q_{\text{min}}$: Minimum capacity

- **Reserve margin constraint**
  The newly added generation unit plus the existing generation unit in the each period should satisfy reserve margin due to network security. Therefore, this constraint is a national constraint and state constraint. In this paper, range of reserve margin variation is taken 1.1 to 1.3 of peak demand and can be written as the following inequality constraint:

$$
(1 + r_{\text{max}}) D_{\text{K}} \leq \sum_{j=1}^{G} P_{N,i}^k \leq (1 + r_{\text{min}}) D_{\text{K}}
$$

(6)

Where

- $r_{\text{min}}$: Minimum reserve margin in interval K
- $r_{\text{max}}$: Maximum reserve margin in interval K

$D_{\text{K}}$: Demand (Mw) in interval K

- **Reliability constraint**
  Reliability is a state constraint. Reliability is approximately a complicated national constraint. In
this paper, reliability is considered in the form of loss of load expectation (LOLE) index. In order to have a reliable system, the LOLE of system should be smaller than a specified value. Accordingly the reliability constraint can be expressed as follows

\[ E^k_N < M \text{ hours/ year} \quad (7) \]

Where

\[ E^k_N : \text{LOLE value of the N-th state in interval K} \]

4 Hybrid DP/GT model description

For the master level of GEP problem, GT is implemented based on Cournot model. In the Cournot model, each firm chooses an output quantity to maximize profit. Firms are assumed to produce homogeneous goods that are not storable. So all quantities produced are immediately sold. Market price in the model is determined through an auction process that equates industry supply with aggregate demand. The model also assumes that all firms in the industry can be identified at the start of the game, and that decision-making by firms occurs simultaneously. In the hybrid MGT/PSO algorithm, essential data which consist of MCP, limitation of mix fuel, reserve margin, and reliability are broadcasted by regulatory body to each GENCO. In the slave level, each GENCO individually carry out GEP by PSO to obtain its own maximum profit while assuming that the other GENCOs don’t intend to have any GEP.

The results of decision making of each GENCO are declared to regulatory body, including the total capacity of new generation unit to be constructed. Afterward, the regulatory body in the master level checks the national constraints ((4) to (7)). If the GEP results of GENCOs satisfy national constraints, the regulatory body will accept results of GEP. Otherwise, the results of GENCOs will be discarded. In both cases however, the results of all GENCOs are anonymously declared by the regulatory body. Currently, in the slave level, each GENCO accomplish a new GEP, considering the last GEP pattern from other GENCOs and return its new results of GEP to the regulatory body, again. This manner is a game theory based on Cournot model. The above-mentioned process will be continued iteratively until no player (GENCO) changes its own planning. In other words, the procedure will be done until the game theory reaches to the Cournot equilibrium. Fig.2 shows the diagram of hybrid GT/DP model for solving the GEP problem in pool market.

5 Case study

The data is adopted from [11] and modified. The total capacity of system is 4100MW before planning and the system includes three GENCOs. The technical and economical data of GENCOs are taken in Table 1. The forecasted peak load in each interval (year) is shown in Table 2. With the DP method, we will take 2 years as the interval. The GEZ horizon is considered six year that is in fact a three two-year period horizon. There are 7 types of candidate generating units that their data are presented in Table 3. The capacity constrains i.e. (2), for each GENCO is assumed 1500 MW. The fuel mix ratio (\(\beta\)) and demand factor (\(\alpha\)) are taken 0.1, 0.001, respectively. The MCP declared by the regulatory body in the planning horizon, is 9 $/MWh, 10 $/MWh and 12 $/MWh in first, second and third period, respectively. With the DP method is used all states and paths. In other hand, we have applied complete enumeration. Therefore, the result of GEP is optimum absolutely and no approximation exists in the solution procedure.

Thus, in the proposed hybrid GT/DP algorithm, Cournot equilibrium takes place in the GT procedure of master programming with high speed. So that the results show in Fig. 3, the Cournot equilibrium is reached after five iterations. The result of GEP by each GENCO is presented in Table 4. Table 4 also indicates that all GENCOs have approximately equal total added capacity over the time horizon despite the fact that the first GENCO has the most profit.
In other words, although the first GENCO can be obtain more profit by increasing its total added capacity; constraint (5) limits the total capacity of first GENCO, preventing the market power of the first GENCO of system and higher profit of GEN.1, it can’t force own market power to other GENCOs. Therefore, can’t devote total expansion to increase capacity of own generation unit.

Table1. The technical and economical data of GENCOs

<table>
<thead>
<tr>
<th>No. of units</th>
<th>Unit type</th>
<th>Capacity (MW)</th>
<th>Fuel Cost ($/KWh)</th>
<th>Maintenance cost ($/MW)</th>
<th>f.o.r</th>
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<tbody>
<tr>
<td>GEN.1</td>
<td>4 Hydro</td>
<td>200</td>
<td>0</td>
<td>245</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2 Nuclear</td>
<td>650</td>
<td>2.41</td>
<td>113.75</td>
<td>0.055</td>
</tr>
<tr>
<td>GEN.2</td>
<td>2 Coal#1</td>
<td>400</td>
<td>4.21</td>
<td>450</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>2 Coal#2</td>
<td>200</td>
<td>4.21</td>
<td>516</td>
<td>0.15</td>
</tr>
<tr>
<td>GEN.3</td>
<td>2 Oil</td>
<td>300</td>
<td>11.3</td>
<td>195</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>2 Cambu. turbine#1</td>
<td>50</td>
<td>12.16</td>
<td>245</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>4 Cambu. turbine#2</td>
<td>25</td>
<td>12.15</td>
<td>140</td>
<td>0.0075</td>
</tr>
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Table2. Forecasted peak demand

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
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<tbody>
<tr>
<td>Peak demand (MW)</td>
<td>3550</td>
<td>5500</td>
<td>6800</td>
<td>8200</td>
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</table>

Table3. The technical and economical data of candidate generating unit

<table>
<thead>
<tr>
<th>Unit type</th>
<th>Capacity (MW)</th>
<th>Capital cost ($/KW)</th>
<th>Fuel cost ($/KWh)</th>
<th>Maintenance cost ($/MW)</th>
<th>Construction limit in each period</th>
<th>Life time (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>650</td>
<td>625.5</td>
<td>2.41</td>
<td>113.75</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Coal#1</td>
<td>400</td>
<td>645</td>
<td>4.21</td>
<td>450</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Coal#2</td>
<td>200</td>
<td>595</td>
<td>4.21</td>
<td>516</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>Oil</td>
<td>300</td>
<td>255.75</td>
<td>11.3</td>
<td>195</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>Cambu. turbine#1</td>
<td>50</td>
<td>152</td>
<td>12.16</td>
<td>245</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Cambu. turbine#2</td>
<td>25</td>
<td>100</td>
<td>12.15</td>
<td>140</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 2. The diagram of GEP solution by using GT/DP
Table 4. Result obtained by hybrid GT/DP method for GEP

<table>
<thead>
<tr>
<th>Unit type</th>
<th>year</th>
<th>Nuclear</th>
<th>Coal#1</th>
<th>Coal#2</th>
<th>Oil</th>
<th>Combu. turbin#1</th>
<th>Combu. turbin#1</th>
<th>profit $ ×10^5</th>
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<td>1</td>
<td>1</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td></td>
<td>2009</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>GEN.2</td>
<td>2007</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2009</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2.0105</td>
</tr>
<tr>
<td></td>
<td>2011</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2.5640</td>
</tr>
<tr>
<td>GEN.3</td>
<td>2007</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>1</td>
<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
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<tr>
<td></td>
<td>2011</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>2.5640</td>
</tr>
</tbody>
</table>

6 Conclusion
This paper proposed a new hybrid GT/DP algorithm for GEP problem in pool market in the form of master and slave levels. For a given time horizon, the introduced method not only determine the required power plant installation of the interest horizon, but it also can successfully estimate the required power plant installation of any arbitrary year before the horizon in a correlating manner, which can be named as a multi-time horizon GEP. In this paper, based on pool market framework, elasticity in MCP for a long term horizon is also applied. With this regard, the expansion planning of each GENCO decreases MCP, resulting in an efficient power market with low price of electricity in long term period. In this paper, we accomplished planning for three periods of two years by using the hybrid DP/GT algorithm introduced in master/slave program. In slave program, we used DP with whole enumeration for self-optimization. The DP with whole enumeration reaches to optimum results and there is no approximation.

7 References