Generation Expansion Planning in a Pool Based Electricity Market, using Game Theory and Genetic Algorithm

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Abstract—**Restructuring has changed purpose of generation expansion planning (GEP) from being cost-minimization to profit-maximization. In this paper, we introduce a new formulation for objective function of generating companies (GENCOs) GEP problem in pool electricity market which includes the revenues of energy and capacity reserve markets and costs of fuel, investment, O&M, outage and emission tax. Moreover, in order to solve GEP problem with above objective function, an algorithm are introduced that use game theory and genetic algorithm for market modeling and optimization of GENCOs objective functions, respectively. To calculate the generation levels of generating units and long-term market price, we have used the traditional probabilistic production costing (PPC) which is modified to be used in competitive electricity market.**

Keywords-generation expansion planning; pool electricity market; game theory; genetic algorithm;

I. NOMENCLATURE

B_i : Expected profit of i-th GENCO, [$]
T : Number of periods (years)
$R_{i,t}$: Revenues, [$]
$I_{i,t}$: Capital costs, [$]
$F_{i,t}$: Fuel costs, [$]
$M_{i,t}$: Operation and maintenance (O&M) costs, [$]
$O_{i,t}$: Outage costs, [$]
$T_{i,t}$: Emission tax, [$]
k : Rank of generating units
$\pi^t_{k,n}$: Energy price in n-th iteration of game, [$/MWh]
$e^t_{k,i}$: Energy generated by k-th units, [MWh]
$\pi^t_{r,n}$: Reserve price in n-th iteration of game, [$/MW]
$r^t_{k,i}$: Capacity reservation decision of k-th units, [MW]
q_k : Forced outage rate (FOR) of k-th units
ρ_k : Availability rate of k-th units
T_h : Number of hours in each planning period
$ELDC$: Equivalent load duration curve
$C^t_{e,k,i}$: Capacity of k-th units committed in energy market
MC_k : Marginal cost of k-th units, [$/MWh]
T_k : Participation time of k-th units in energy market
$D(\pi)$: Total demand as a function of price, [MW]
A : Slope of demand function
B : Demand at zero price
D_{base} : Forecasted demand, [MW]
π_{base} : Base price of energy market, [$/MWh]
ε : Demand elasticity factor
ρ_{sys} : Average availability rate of system
C^t : Total installed capacity in system, [MW]
q^t : Average customer outage cost, [$/MWh]
$U^t_{k,i}$: Expansion decision of k-th units, [MW]
$C^t_{inv,k}$: Unitary construction cost of k-th units, [$/MW]
fc^t_k : Unitary fuel cost of k-th units, [$/MWh]
UF^t_k : Unitary fixed O&M cost of k-th units, [$/MW]
UV^t_k : Unitary variable O&M cost of k-th units, [$/MWh]
$C^t_{k,i}$: Available capacity of k-th units, [MW]
π^t_o : Unitary outage cost (equal with RTP), [$/MWh]
TR^t : Unitary rate of emission tax, [$/kg]
$EM^t_{k,i}$: Emission of k-th units, [kg]
Lim^t_i : Limitation of investment, [$]
$N^t_{k,i}$: Number of new added k-th units
α : Fuel mix ratio
$U^t_{p,j}$: Aggregated capacity of new peak type units, [MW]
$U^t_{b,i}$: Aggregated capacity of new base type units, [MW]
$r^t_{\min}$: Minimum reserve margin
$r^t_{\max}$: Maximum reserve margin
G : Number of GENCOs
$LOLP^t$: Loss of load probability index
$EENS^t$: Expected energy not supply index, [GWh]

It should be noted that i and t in the above symbols indicate related i-th GENCO and t-th year, respectively.

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II. INTRODUCTION

Generation expansion planning (GEP), is a large-scale, nonlinear, discrete, dynamic and highly constrained optimization problem that determines which generating units should be constructed and when should be committed online over the planning horizon in such a way that installed capacity meet forecasted demand [1-4]. The sites locations and other factors related to transmission network are commonly analyzed separately and after a size for expansion has been decided [5].

In traditional monopolistic framework, generation expansion activities has been performed by a vertically integrated utility and in order to meet long-term reliability criteria. The objective of monopolistic GEP problem, has been the minimization of the expected sum of yearly discounted costs which incorporate construction costs, operating costs, salvage value, and so on [6]. However, constraints such as reserve margin, fuel mix, reliability criteria and environmental limitations, must be considered [7]. Various models for traditional GEP, were developed to fulfill the minimum cost through several optimization algorithms [2, 3] and probabilistic production costing (PPC) [8].

In recent years, power generation industry in many countries has undergone restructuring from being a state monopoly to deregulated liberalized markets. One cause for restructuring is the belief that electricity generation no longer possesses properties of a natural monopoly due to technologically driven decreases in efficient plant sizes. Diminishment of scale of economies in generation has broken the utility industry into generation firms who compete among each other to sell power, which is transmitted by a monopoly high-voltage transmission system to independent distribution firms and local customers [9].

These changes affect long-term expansion planning, as investment decisions are now taken by private investors leading to a more reduced level of centralized coordination [10].

The other changes which restructuring has been made in GEP process, Include [1,9,10]:

- Change of the purpose from cost-minimization to profit-maximization
- Considering the demand effect on the electricity prices (introduction of Demand Response)
- Appearance of strategic interaction and gaming among firms involved in the GEP process
- The shortening of planning horizons due to the elimination of traditional guaranteed return on investment
- Considering the incomplete information structure of the market. This is usually handled by using the game theory.

GEP methods in the restructured power system depend on the model of electricity market (i.e. primary market or pool market). In primary competitive model, several independent power producers (IPP) sell their power only to the utility, but in the pool competitive model, each private generating company (GENCO) would compete with other GENCOs for profit maximization [11].

Unlike traditional approaches, competitive GEP is very complex due to the conflicts among generating companies [12].

Essentially, the competitive GEP problem in the pool electricity market, can be modeled as non-cooperative game in which GENCOs make decision about their capacity expansion to maximize their expected profit from future markets and competing with other GENCOs [13]. Profit function can be defined as the difference between revenues earned and costs incurred from providing electric service. Usually revenues are based on energy market payments and costs are based on capital and operating costs [5, 6, 10, 11, 12, 13].

In this paper, we analyze the generation expansion planning in the pool markets. We introduce a new formulation for the objective function of GEP problem in a pool market. Each GENCO uses genetic algorithm (GA) to optimizes his own objective function of GEP problem, dynamically for all years of planning.

Afterwards, GENCOs submit their plans to the regulatory body called as Independent System Operator (ISO) [12]. one of the objectives of ISO is stabilizing market through coordination between GENCOs by providing long-term market information to them, which can prevent extreme over/under investments in the electricity market [6,12]. ISO clears the market and determines energy and reserve market prices. Prices and other necessary information for planning are transmitted to each GENCO, separately. The ISO is also responsible for considering reliability constraints, reserve margin and national security [11].

In this paper, we use Cournot game for modeling the incomplete structure of the pool electricity market. Players are private power generation companies. Vector of players' decisions for which no player changes its plan after an entire round of optimization is called a Cournot equilibrium. Solution algorithm of GEP game iterates until such an equilibrium is found [1].

III. FORMULATION OF GEP IN POOL MARKET

In the pool electricity market, the goal of each GENCO in GEP is maximizing expected profit from future markets and competing with other GENCOs. Therefore, the GEP problem for the i-th GENCO can be written as (1) in which revenues consist of energy and capacity reserve markets payments and costs include capital costs, fuel costs, operation and maintenance costs, outage costs and emission tax.

$$Max\ B_i = \sum_{t=1}^{T} \left(\overline{R}_{i,t} - \left[\overline{I}_{i,t} + \overline{F}_{i,t} + \overline{M}_{i,t} + \overline{O}_{i,t} + \overline{T}_{i,t} \right] \right) \qquad (1)$$

The bar over the symbols show discounted values to a reference date at a given discount rate. We have used linear depreciation method to calculate cash flow for the investment plans. The total profit of the i-th GENCO is the summation of profits in all years of planning horizon. Consequently, the profit optimization problem of each GENCO becomes a