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GENCOs' Long-Term Expansion Model

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Abstract— **Traditionally, the objective in undertaking a Generation Expansion Planning (GEP) process has been to minimize the expected sum of yearly discounted costs (incorporate i.e., construction costs, operating costs, salvage value, etc.). Now, the objective is to apply GEP to today's competitive electricity markets in order to maximize the profits of individual GENCOs (i.e., the revenues based on market prices and capital and operating costs) and minimize the impacts of competitors' conflicting objectives. This paper introduces a long-term expansion model for GENCOs operating in the deregulated electricity environment. The model considers uncertainty, generation capacity limits, and expansion rate and investment during the expansion period. Numerical examples are provided.**

***Index Terms*— Profit maximization, generation expansion planning, demand forecast.**

I. Introduction

OPTIMAL long-term GEP is traditionally perceived as the determination of the minimum-cost capacity addition plan that meets forecasted demand within a pre-specified reliability criterion over a planning horizon [1]. Capacity expansion models have long been utilized in both the power sector and the operations research literature. The GEP problem is considered difficult to solve for several reasons, including unreliable results from the uncertainty associated with the input data (i.e., forecasts of demand for electricity, economic and technical characteristics of new evolving generating technologies, construction lead times, and governmental regulations) and the reality that often several conflicting objectives must be considered [2].

In centralized electricity systems, various models for generation planning were developed to identify the minimum cost through optimization algorithms and probabilistic production costing (PPC). Park presented a mathematical formulation based on the WASP model [1]. The high non-linearities of a GEP problem originated from the probabilistic production costing simulation and a set of physical/engineering nonlinear constraints. To solve this complicated problem, different methods were applied: the most widely used being dynamic programming (DP). Bloom used Generalized Bender's Decomposition (GBD) algorithm to sub-divide the master GEP problem into a set of sub-problems, which could then be solved in an iterative way to find the optimum cost [1]. The issues of risk and uncertainty that are usually associated with GEP were mainly addressed by stochastic optimization, a multi-stage stochastic electric utility planning model that compares the flexibility benefits of different electric utility resources when dealing with demand uncertainty. A global optimization technique using a Genetic Algorithm (GA) has also been successfully applied to economic dispatch and other power system functions [1].

However, solving for GEP has been totally redirected since the introduction of market deregulation and competition. Although assuming "perfect" competition is viable for these new markets, a more suitable hypothesis uses an oligopolistic market in which each generator can influence prices [3]. Therefore, the problem of power GEP has been reformulated from cost-minimization to maximizing the total expected profits of individual GENCOs over a planning horizon, while guaranteeing power system reliability through cooperation among the GENCOs [4].

Some methods of GEP use the historical available market information to form a statistical background for the problem and then apply an inverse optimization procedure to identify the expansion alternatives [5]. A hierarchical multi-criteria game model has been studied (hierarchical games belong to a multi-step game class and are used to model systems with hierarchical structure under conditions of non-coincident interests). Hierarchical structure is determined by a series of regulation levels that follow each other in order of a definite priority. In the mathematical formulation the hierarchical games are classified by the number of levels and character of vertical ties. [6]. Non-cooperative game theory using the Cournot model has been used to formulate a GEP model that may characterize expansion planning in a competitive regime, particularly in pool-dominated generation supply industries. [7]. Optimal long-term electric power capacity strategies with capacity options have also been used. For example, GENCOs can sign contracts with Distribution Companies (DISCOs) that take the form of capacity options that may or may not be executed by the DISCOs at some pre-specified maturation date [8]. Furthermore methodologies that use several uncertainty factors such as demand growth, fuel cost, delay in project completion, financial constraints, etc., have been applied. This solution-based approach uses stochastic optimization techniques, decision analysis, and multi-objective tradeoff analysis [9].

An investment planning model for electricity generation expansion in a hydro-dominated environment [10] was developed to rigorously valorize the large hydroelectric potential resources of Cameroon. Based on GBD the decomposition approach proposed allows each component of

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the problem (investment and operation) to be conveniently modeled and solved by adapted methods.

Finally, resource planners often focus on identifying the resources to be chosen rather than the prices to be charged. However, prices and their effects on loads can be included in resource integration models by adding two types of constraints: a revenue requirements equation and a demand curve.

In this paper, a long-term expansion model for GENCOs is presented. The model accounts for uncertainty, generation capacity limits, expansion rate and investment during the expansion period. The paper is organized as follows: In section II the formulation of the model is presented. Numerical examples are reported in Section III. Conclusions are presented in Section IV.

II. Generation Expansion Model

We can distinguish GENCOs' short-term and long-term operating models by their decision-making time scales, for short-term the time scale consist in few weeks or few month (no time value of money is involved) and the long-term the time value of money must be into account since five to ten years. But for both cases:

- GENCOs try to maximize their profits.
- Their activities are limited by economic and technical constraints.
- Their activities are influence by demand and fuel prices.

The following analysis assumes an oligopolistic market, currently the most common market structure. It assumed that the expansion rate is proportional to the difference between the marginal cost and the price when the difference is positive. There will be no expansion when the difference is zero or negative. Therefore:

$$Pg_i(t+1) - Pg_i(t) = \max\{\lambda(t) - C'(Pg_i(t)), 0\} \quad (1)$$

where t is the time index, i is the index for the number of GENCOs, $Pg_i(t+1)$ and $Pg_i(t)$ are the generation outputs for the time period $t+1$ and t, respectively, $\lambda(t)$ is the demand function at period t and $C'(Pg_i(t))$ is the marginal cost.

If competition is introduced in the market, it is believed that the electricity price may fall, but we note that this is unlikely, due to the competition among the players, GENCOs' strategic behavior to maximize profits, gaming, congestion, etc. [11].

In the real world, a GENCO will try to maximize its total present value of future profit according to its own internal forecasts of future demand. Clearly, demand forecasting is one of the most important tools in a GENCO's analytical toolbox. The forecast typically must be for power (kW), energy (kWh), and load variation for time intervals within a year, for all years of the study [12]. For the purpose of this analysis is used forecast demand for time periods. If much effort is to be devoted to analyzing the alternative expansion possibilities, the demand forecast also merits significant effort.

Various technologies are currently available for modeling electrical generating system expansion. Each has a unique set of characteristics that must be considered from a system viewpoint to determine the mix of future additions that provides the optimal outcome based upon the stated objectives.

Our formulation omits the transmission network; therefore the load is considered as the set of generators connected in one node with technology options as shown in Fig 1.

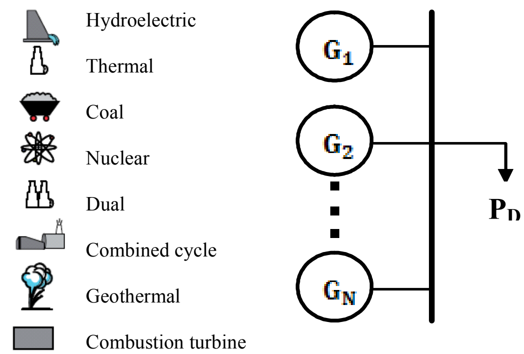

Fig.1. Set of generators connected in one node

After determining future demand via its forecasting, a GENCO calculates the possible future power price according to the demand functions.

$$\lambda(t) = a_d - b_d Pd(t) \quad (2)$$

where a_d and b_d are the market-demand parameters, $P_d(t)$ is the demand forecast for time period t.

Next, it tries to maximize its future profit by:

$$\max = \sum_t \pi(t) = R(t) - C(t) \quad (3)$$

This expression the profit $\pi(t)$ of GENCOs at period t is the difference between the revenue $R(t)$ in the time period t and the economic cost $C(t)$ in the time period t, where the total cost are represented by variable cost and fixed cost, the variable cost includes fuel cost and operation cost, and the fixed cost includes investment opportunity cost and fixed asset expenditure.

The production cost function $C(Pg_i(t))$, is expressed as is showed in the next equation:

$$C(Pg_i(t)) = d_i + e_i(Pg_i(t)) + f_i(Pg_i^2(t)) \quad (4)$$

The cost function here is quite different from the short-term cost function, where d_i, e_i and f_i are the coefficients of production cost function; the depreciation costs should be considered subject to expected profit maximization constraints:

$$\max \sum_t \pi(t) = \sum_t \gamma(t)\{\lambda(t)Pg_i(t) - [d_i + e_i Pg_i(t) + f_i Pg_i^2(t)] \quad (5)$$

where $\gamma(t)$ is the discount factor.

The GENCO is uncertain about the future profit; it may want to maximize the expected future profit present value, including the possibility of the future profit for time period t, denoted by $\rho(t)$.

$$\max \sum_t \pi(t) = \sum_t \rho(t)\gamma(t)\{\lambda(t)Pg_i(t) - [d_i + e_i Pg_i(t) + f_i Pg_i^2(t)]\} \quad (6)$$

This expression is for maximizing profits for one GENCO with one unit. For a GENCO with several units, we use:

$$\max \sum_t \pi(t) = \sum_i \sum_t \rho(t)\gamma(t)\{\lambda(t)Pg_i(t) - [d_i + e_i Pg_i(t) + f_i Pg_i^2(t)]\} \quad (7)$$

Note that the production cost function of the GENCOs $C(Pg_i(t))$ is the quadratic form, which is the type of function used in our analysis.

There may be constraints for the maximum generation capacity (such as the stream amount for a hydro generation plant and pollution constraints for thermal generation). Thus:

$$Pg_i(t) \le Pg_i^{\max} \quad (8)$$

The generation expansion rate cannot exceed the maximum expansion rate $Pg_i^{\max}$.

$$Pg_i(t) - Pg_i(t-1) < \Delta P_i^{\max} \quad (9)$$

The total investment during this expansion period cannot exceed the total investment capital limitation:

$$\sum_t I[Pg_i(t)] \le Inv \quad (10)$$

where $I[Pg_i(t)]$ is the investment expense in the period t determined by generation and this cannot be more that .

Expansion decisions considered in every time period are the installation of diverse kinds of thermal units in the node and limitations by the planner who can also limit the maximum and minimum generation capacity according to the profit of each generator in every time period.

The model studies the tendency of technologies and their profits and then it can be applied to for analyzing geographically defined nodes or areas. The optimal GEP will use both analyses and add a third step to check electric system reliability. Fig. 2 illustrates an optimal GEP.

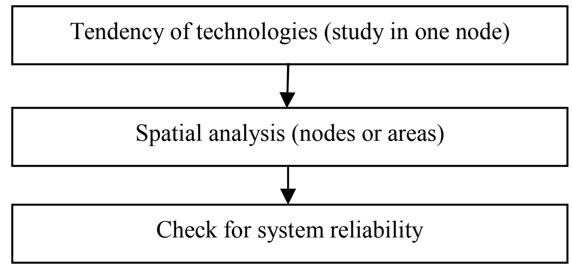

Fig.2. Steps of an optimal GEP.

III. Numerical Examples

Most of the electricity generated worldwide is produced from oil, coal, natural gas, water and nuclear. This analysis only takes into account thermoelectrical generators.

The production cost data shown in Table I has been taken from reference [13] and modified. Every producer uses a different fuel for producing electricity.

TABLE I
PRODUCERS' COST DATA

Producer No.	d_i	e_i	f_i	$Pg^{\min}$	$Pg^{\max}$
1 (oil)	500.00	5.3	0.004	200	450
2 (coal)	400.00	5.5	0.006	150	350
3 (natural gas)	200.00	5.8	0.009	100	225

where $Pg_i^{\min}$ and $Pg_i^{\max}$ are the minimum and the maximum generation capacity of GENCO i respectively.

The generators are connected in one node as shown in Fig. 3.

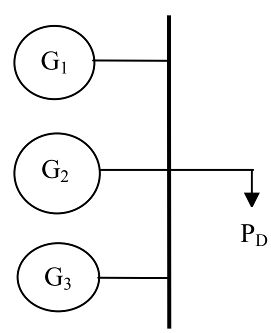

Fig.3. Set of three generators connected in one node.

The expected demand function parameters for every time period are listed in Table II. The same demand function is retained for all of the cases, but the market demand parameters are going to be different.

TABLE II
MARKET DEMAND PARAMETERS FOR TIME PERIOD

Period	*a*	*b*
1	337	0.31
2	345	0.28
3	168	0.12
4	174	0.12
5	170	0.12
6	178	0.12
7	220	0.15

The demand forecast is showed in the Fig. 4; this parameter is considered because the GENCO needs to calculate the possible future price of power according to the demand function.

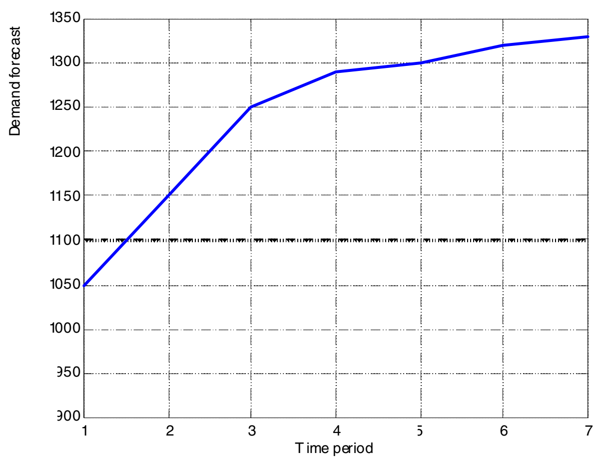

Fig.4. Demand forecast for time period

The Fig. 5 shows the different expected prices of the fuel in every time period and their fluctuation. The power producer must take into account both price and demand uncertainty when making decisions [14].

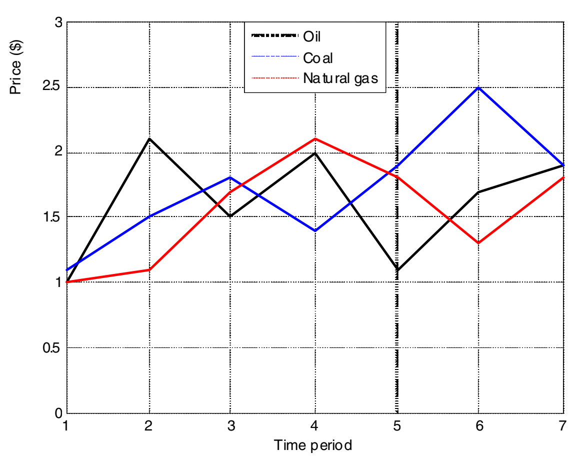

Fig.5. Prices of primary energy in every time period

In this case the discount factor, which is used into the objective function if there is not certain about the future profit have a valor of one also the possibility of the future profit for time period. Table III lists the simulation's results. Obviously, each GENCO makes its decisions on future capacity investments without exchanging information with other GENCOs. However, regulations may be in place concerning the total investments to preserve national energy fuel mix strategies or to prevent over/under capacity investments in the market [15].

TABLE III
GENERATION OF EACH GENERATOR FOR EVERY TIME PERIOD

Period	Generation MW (oil)	Generation MW (coal)	Generation MW (natural gas)
1	553.32	278.53	218.14
2	269.64	411.66	468.68
3	735.81	318.50	195.67
4	487.93	637.32	164.73
5	1006.76	185.94	107.29
6	695.58	157.32	467.08
7	635.86	407.24	286.88

According with maximum and minimum generation capacity of each generator and with the obtained data about the generation for every time period the expansion capacity of each GENCO is showed in the Table IV.

TABLE IV
EXPANSION CAPACITY OF EACH GENERATOR FOR EVERY TIME PERIOD

Period	Expansion capacity MW (oil)	Expansion capacity MW (coal)	Expansion capacity MW (natural gas)
1	103.32	0	0
2	0	61.66	243.68
3	182.49	0	0
4	0	255.66	0
5	270.95	0	0
6	0	0	0
7	0	0	0
Total	556.76	317.32	243.68

The result of expansion capacity for each GENCO exceed the demand, due to there is not constraint in the expansion rate then, it is possible that the cost of building too much generating capacity could be affect to the customers with increasing of price electricity.

Knowing the generation of each GENCO, we can now obtain the profits of the generators in every time period in monetary units Ȓ . Table V lists the profits.

TABLE V
PROFIT OF EACH GENERATOR FOR EVERY TIME PERIOD

Period	Profits Ȓ (oil)	Profits Ȓ (coal)	Profits Ȓ (natural gas)
1	1705.94	805.70	615.14
2	3442.58	4964.02	4947.04
3	6679.17	2972.67	1842.61
4	5330.02	5894.24	1763.22
5	4204.55	973.06	576.21
6	7511.47	1669.83	4282.28
7	7547.87	4713.58	3276.51

Expansion decisions considered in every time period are the installation of diverse thermal units in the node and limitations by the planner who can also limit the maximum and minimum generation capacity according to the profit of each generator in every time period.

Now is considered that $\gamma(t)$ and $\rho(t)$ have certain expected values as is listed in the Table VI.

TABLE VI
EXPECTED VALUES OF DISCOUNT FACTOR AND POSSIBILITY OF FUTURE PROFIT

Period	$\gamma(t)$ (%)	$\rho(t)$ (%)
1	5	94
2	4	97
3	3	98
4	0	95
5	2	99
6	8	96
7	1	95

The expected profits for each GENCO in every time period accounting for the discount factor and the possibility of future profit are listed in the Table VII

TABLE VII
PROFIT OF EACH GENERATOR FOR EVERY TIME PERIOD CONSIDERING EXPECTED VALUES OF $\gamma(t)$ AND $\rho(t)$

Period	Profits ₨ (oil)	Profits ₨ (coal)	Profits ₨ (natural gas)
1	1523.40	719.49	549.32
2	3205.73	4622.50	4606.68
3	6349.22	2825.82	1751.59
4	5063.52	5599.53	1675.06
5	4079.25	944.06	559.04
6	6634.13	1474.79	3782.11
7	7098.77	4433.12	3081.56
Total	33954.02	20619.31	16005.36

According to each GENCO's expansion capacity shown in Table IV and considering that ₨ 50 of investment is required for expanding/installing each MW, the total profits in the case for all of the GENCOs through the conclusion of the time period appear in Table VIII.

TABLE VIII
TOTAL PROFIT OF EACH GENERATOR WITH EXPANSION CAPACITY INSTALLED

Profits ₨ (oil)	Profits ₨ (coal)	Profits ₨ (natural gas)
6116.02	4753.31	3821.36

Now, considering the constraint of the rate of expansion and the maximum generation capacity of each GENCO, the expansion rates for GENCOs 1, 2 and 3 are 50 MW, 40 MW and 30 MW respectively. The generation for every GENCO can be found if GENCOs 1 and 3 expand their generation capacity in the first time period and GENCO 2 expands its capacity according to the behavior of GENCOs 1 and 3. Table IX lists the generation capacity.

TABLE IX
GENERATION OF EACH GENERATOR TAKING INTO ACCOUNT THE EXPANSION RATE FOR EVERY TIME PERIOD

Period	Generation MW (oil)	Generation MW (coal)	Generation MW (Ngas)
1	500.00	295.00	255.00
2	500.00	395.00	255.00
3	550.00	445.00	255.00
4	550.00	485.00	255.00
5	600.00	445.00	255.00
6	600.00	435.00	285.00
7	600.00	445.50	285.00

Note that the expansion capacity for each GENCO is less when GENCOs 1 and 3 expand their capacity in the first period than the results shown in Table IV. Hence, the expansion decisions are made according to Table III, where we observe that the optimum moments for the expansion of GENCO 1 are the time periods 1, 3 and 5, and for GENCO 3 the time periods are 1 and 6, because the profits shown in Table V are greater in the next period. We note that GENCO 2 must wait upon the behavior of the others to make its expansion decisions, Thus, its optimum moments are time periods 2, 3 and 4. Decisions to expand in all of these time periods provide balance between demand and expansion capacity and avoid overbuilding. The expansion of the GENCOs in every time period appears in Table X.

TABLE X
EXPANSION CAPACITY OF EACH GENERATOR FOR EVERY TIME PERIOD ACCORDING THE EXPANSION RATE

Period	Expansion capacity MW (oil)	Expansion capacity MW (coal)	Expansion capacity MW (Ngas)
1	50.00	0	30.00
2	0	45.00	0
3	50.00	50.00	0
4	0	35.00	0
5	50.00	0	0
6	0	0	30.00
7	0	0	0
Total	150.00	130.00	60.00

Finally the profits for the GENCOs considering the expansion capacities installed in the time period as shown in Table X and the generation of each generator taking into account the expansion rate, the discount factor and the possibility of future profit shown in Table VI are listed in Table XI.

TABLE XI
PROFIT OF EACH GENERATOR FOR EVERY TIME PERIOD

Period	Profits ₨ (oil)	Profits ₨ (coal)	Profits ₨ (natural gas)
1	1600.00	847.85	668.27
2	6349.99	4786.34	3090.77
3	5275.00	3974.35	2325.77
4	5935.00	4833.15	2631.77
5	3280.00	2195.35	1305.77
6	6640.00	4598.15	3001.97
7	7180.00	5086.85	3258.47
Total	36259.99	26322.04	16282.79

The total profits considered that each GENCO's expansion capacity is installed in the period as indicated in Table X, are listed in Table XII.

TABLE XII
TOTAL PROFIT OF EACH GENERATOR WITH EXPANSION CAPACITY INSTALLED

Profits $\bar{R}$ (oil)	Profits $\bar{R}$ (coal)	Profits $\bar{R}$ (natural gas)
28759.99	19822.04	13282.79

Since the profits in this case are greater, because the investment for expansion capacity is less than previously, it is preferable to expand capacity in the first period and then observe the behavior of the other GENCOs.

IV. CONCLUSIONS

The expansion capacity and profit for different generators in different time periods are shown, taking into account fuel prices, market demand parameters, and forecast demand, to obtain some expected values for generation expansion planning. The decisions taken by the planner must consider the existing system, rehabilitation, removal/dismantling, and programmed decisions.

We suggest that future research should examine stochastic formulation in order to identify other aspects of long–term expansion process, constraints like reserve margin, fuel mix ratio, and the like.

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BIOGRAPHIES

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