Competitive Generation Expansion Planning Using Imperialist Competitive Algorithm

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Abstract: Deregulation in the electricity industry leads to new challenges in Generation Expansion Planning (GEP), due to the competition among the Generation Companies (GENCOs) and opposing objectives of GENCOs and policy makers. This paper presents the GEP problem in competitive environment and applies the Imperialist Competitive Algorithm (ICA) to solve this problem. The objective of each GENCO is maximization of its profit while the regulatory body is concerned with market and system stabilization trough providing the appropriate signals to investors to avoid the over/under investment. Other objectives of the regulatory body are optimization of generation capacity, maintaining system and national security and maximization of the social welfare. In order to model the competition between the GENCOs and opposing objectives in this problem, the GEP problem is modeled as a Cournot game with Nash equilibrium. The GEP problem is solved iteratively by self-optimizing of each GENCO using ICA and satisfying the regulatory body in Cournot model. The proposed algorithm is tested on a simple case and the results are compared with those drawn in previous works. The obtained results demonstrate the effectiveness of the proposed ICA-based method.

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1. Introduction

The fundamental differences between the today's power systems and those before the era of restructuring are mostly due to the socio-economical aspects rather than technical issues. The fast changes in financial structure of power systems have led to wide variations in technical structure and various progresses in these systems. One of the main differences is that traditionally, in least cost Generation Expansion Planning (GEP) the problem was to identify the optimal timing, location, size and technology of new generation which minimize the total construction cost of the new units and satisfy the load balance and security constraints [1-2]. However, competition among the Generating Companies (GENCOs) is the main goal of deregulation and with the introduction of competition several changes have been taken place in the electric power industry [3-4]. In a competitive power system, expansion participants are profit maximizing companies. New technologies in power generation and information technology also affect the GEP problem. Opposing criteria of market participants and regulatory body and conflicts among GENCOs are the main differences that make the competitive GEP a more complex problem to solve comparing to the classic GEP problem.

It is difficult to formulate these changed GEP environments including GENCOs and the regulatory body in a mathematical form and solve the problem using conventional optimization technique [5-6]. GENCOs submit their construction offers to Independent System Operator (ISO) based on their prediction of the future load share and different signals such as price predicted by ISO. ISO is concerned with optimal generation capacity (to prevent over/under capacity investments in the market), system security, reliability and appropriate fuel mix (there are always some regulations on the total capacity of each fuel type.

Here a Coumot model [7] is considered in order to formulate the competitive GEP problem and gaming among ISO and GENCOs, the objective of which is to reach to the Nash equilibrium in an iterative framework in case of existence of such equilibrium. Nash equilibrium is a set of players' decisions in the game such that no player can obtain higher profit by modifying its strategy in the case that other players stick to their equilibrium strategies. Such equilibrium is hard to predict due the nature of the power markets with so many participants each with opposing criteria with the others and ISO and also strategies that are hard to predict. The market may also have no equilibrium point, due to integer variables of GEP problem. It should be also noted that markets are dynamic and in constant motion. However, the decisions may remain near the equilibrium point in the long run. In order to maintain a confident level of security maintaining a proper level of capacity reserve is necessary. System reliability is enforced in this paper via considering Loss of Load Expectation (LOLE) constraint. In order to avoid over and under capacity investment ISO decreases and increases the future price via a proper function suited based on the market structure and previous experiences. In order to avoid the low values of LOLE (lower than a fixed value enforced by social-economical characteristics of the power system and market) a constraint is considered in self-optimization of each GENCO. In this paper each GENCO optimize its strategy at each iteration using Imperialist Competitive Algorithm (ICA) which is an evolutionary computational method that has been used to solve different optimization problems. Like most of the heuristic methods, ICA does not need the gradient of the function in its optimization process and therefore, is suitable to solve the problem which the objective function is not convex and differentiable. ICA is a computer simulation method conceptualized from the humans' social evolution. The aim of each GENCO is maximization of its profit while the ISO is concerned with market and system stabilization trough providing the appropriate signals to investors to avoid the over/under investment and to improve system security. Other goals of the ISO are optimization of generation capacity, maintaining system and national security and maximization of the social welfare. In self-optimization of each GENCO, some constraints which are imposed by the regulatory body should also be considered. In the case of violation of such constraint an appropriate penalty is added to the value of the objective function to avoid such solution.

The contributions of this paper are listed below:

Employment of ICA optimization tool for solving the complex problem of market-based GEP.

Inclusion of reliability in price signal to investors to improve the system security.

Modeling of the market-based GEP problem as a Cournot game with Nash equilibrium.

The rest of this paper is organized as follows. ICA algorithm is presented in section II and proper references are given. Section III discusses the proposed competitive GEP algorithm. The results of application of proposed GEP algorithm on a simple case is presented and discussed in detail in section IV. The concluding remarks are drawn in Section V.

I. Imperialist Competitive Algorithm

Evolutionary optimization methods, inspired by natural processes, have shown good performance in solving complex optimization problems. All of these methods are similar in on aspect that the move from one solution to another is done using rules based upon human reasoning, so the called intelligent. Heuristic algorithms may search for a solution only inside a subspace of the total search region. They are not limited by the search space characteristics like existence of derivative of the objective function and continuity. Several heuristic methods can be addressed such as: particle swarm optimization, simulated annealing, Tabu search and genetic algorithms; each one with some advantages and disadvantages in different areas of the problems. These algorithms are generally inspired by modeling the natural processes and other aspects of species evolution, especially human evolution. But Imperialist Competitive Algorithm has been conceptualized from socio-political evolution of human as a source of inspiration for developing a strong optimization strategy. ICA is a relatively new evolutionary optimization algorithm.

Imperialism is the policy of extending the control of an imperialist beyond its boundaries. It may try to dominate other countries by direct rule or via controlling of markets for goods. ICA is a novel global search heuristic that uses imperialistic competition process as a source of inspiration [8].

This algorithm starts with an initial population (a number of randomly produced solutions). Each solution in the population is called country. Considering the value of objective function as the measure, some of the best countries in the population selected to be the imperialists and the rest form the colonies of these imperialists. In this algorithm the more powerful imperialist, have more colonies. As the competition starts, imperialists try to achieve more colonies and the colonies start to move toward their imperialists. So during the competition the powerful imperialists will be improved and the weak ones will be collapsed. At the end of algorithm just one imperialist will remain. In this stage the position of imperialist and its colonies will be the same. The algorithm steps are summarized as follows. More details about this algorithm can be found in [9-14].

1.Generating Initial Empires: The goal of optimization is to find an optimal solution in terms of the variables of the problem. An array of optimization variable values is called "country". The cost of a country is found by evaluating the objective function for this country. To start the optimization algorithm we generate the initial population of size $N_{country}$. N_{imp} of the most powerful countries are selected to form the empires. Other countries will be the colonies each of which belongs to an empire.

2.Moving the Colonies of an Empire toward the Imperialist: Imperialist countries start to improve their colonies. This has been modeled by moving all the colonies in this empire toward the imperialist. It means that a new country will be generated based on the position of each country in the empire and the distance of this country and imperialist.

3.Finding the Total Power of an Empire: The total power of an empire is mostly affected by the power of its imperialist. However, the power of its colonies of an empire has an effect, on the total power of empire. The mean value of the cost function of other countries in the empire will be added to the value of objective function for the imperialistic with a small coefficient to form the power of each empire.

4.Imperialistic Competition: each empire tries to take the control and ownership of colonies of other empires. This competition brings about a decrease in the power of weaker empires and an increase in the power of more powerful ones slowly. The competition is modeled by choosing a number of weakest colonies of the weakest empires and allow for the empires to compete for acquiring the chosen colonies.

5.After a number of iterations only the most powerful empire will remain and all the countries will be controlled by this imperialist which is the optimum solution of the problem.

The ICA has been successfully applied to solve several problems [15-16]. The results of these studies demonstrate the effectiveness of ICA over other heuristic methods.

II. Generation Expansion Planning Formulation in Competitive Environment

Traditionally the objective of the generation expansion planning aims at building an investment schedule that satisfies the demand and that minimizes the present value of operation and investment costs [17]. However, the investment decision process changed with the development of competition in the power systems since investment on new generation capacity has become a commercial and risky activity. This is mainly because investors are more interested in short-term investment return and are less interested in investing on generation capacity that requires large capital investment and long recovery periods [18].

The generation expansion planning problem in competitive electricity market environment includes the investment decision-making of individual GENCOs whose objectives are the maximization of their own profits. In a fully competitive market, the decision-making of each GENCO on capacity investment is highly influenced by its load-demand forecasting, market share, business strategies. In competitive electricity market all GENCOs should make decisions on their future capacity investments without exchanging information with other GENCOs. However, in order to preserve national energy fuel mix strategies and avoid over/under capacity investments in the market, there can be some regulations on the total investments [19].

Generation expansion planning in competitive environment is also influenced by load uncertainties, restructuring policy and market management instructions. On the other hand, investors should take into account the possible behaviour of the other competitors given the interactions existing in this decentralized decision making process. The formulation of such a complicated decision making process should pay attention to a number of issues such as the change in demand, market prices, variations of regulatory policies and changes of financial and economic data [18].

The generation expansion problem in a competitive environment involves the maximization of the profits of each individual GENCO. Therefore the objective function is as the following.

A. Objective Function

In this paper the generation expansion planning problem for ith GENCO in a competitive environment is formulated. The objective function of the optimization problem is as follows:

$$\max \ Profit_i = (\Pr - C_i) \times P_i \tag{1}$$

Where, $Profit_i$ is the profit of the ith GENCO that is aimed to be maximized. Pr is the price of one MW electric power at the planning horizon; C_i is the total cost of generation of one MW electric power for the ith GENCO. Finally P_i is the quantity of power generated by the ith GENCO.

The price of electric power (Pr) is defined as follows:

$$Pr = const - \alpha \times \left[\sum_{i=1}^{N_{Gen}} P_i \right] \tag{2}$$

Where, Const is the constant value determined by the ISO or regulation authorities. α is the demand coefficient and N_{Gen} is the number of GENCOs in the market who wants to participate in generation expansion planning problem.

B. Constraints

There are several constraints for this problem that make it more complicated and make it harder to find the solution. However in order for result to be applicable these constraints should be considered in the optimization problem.

The constraints considered in this paper include reliability, total capacity in each stage, installation ability and generation mix. The numerical constraints include state constraints and path constraints. The solution should satisfy all these constraints.

Reserve Margin

The selected units to be installed in the power system based on the best solution along with the existing units must satisfy the minimum and maximum reserve margin.

$$\sum_{i=1}^{N_{Gen}} P_i + P_0 \geq (1 + Res_{Min}) \quad (3)$$
$$\sum_{i=1}^{N_{Gen}} P_i + P_0 \leq (1 + Res_{Max})$$

Where, P_0 is the total power produced by the existing generators in MW at the existing year (year zero). Res_{Min} and Res_{Max} are is the minimum and maximum reserve rate criterion, respectively that are considered 20% and 40%.

Reliability

Reliability is a state limit which is the most complicated one of the numerical constraints. The reliability index applied in this paper is Loss of Load Expectation that is called LOLE. For an acceptable solution obtained by the proposed method, its retrieved system LOLE should be smaller than a specified and pre-defined value. This constraint can be formulated as the following:

$$LOLP \leq \varepsilon \quad (4)$$

Where, ε is the pre-defined value that is considered to be 0.001 in this paper.

Upper Construction Limit

Generally based on ISO policies each GENCO has a maximum generation limit. Each individual GENCO should generate power less than or equal to its maximum generation constraint and it is expressed by (5).

$$P_i \leq P_i^{Max} \quad (5)$$

Where, P_i^{Max} is the maximum generation constraint of ith GENCO.

Fuel Mix Ratio Constraint

There are different types of generating units such as Coal, Liquefied Natural Gas (LNG), Oil, and Nuclear in the generation expansion planning problem. To provide national security, ISO imposes some minimum rate fixed for each fuel type.

$$FMR_{Min}^{i} \leq \frac{P_i}{P_i^{Max}} \qquad i = 1, 2, \ldots, N_{Gen} \quad (6)$$

Where, FMR_{Min}^{i} is the minimum fuel mix ratio of ith type of generating units.

III. Simulation Results and Discussions

In this section we present the test system and the results obtained from the proposed method. The proposed algorithm based on ICA for the generation expansion planning problem was implemented using MATLAB R2011a.

A. Test System

The data is adopted and modified from [20]. The generation system includes a mix of several technologies and in the expansion process initial stage the system maximum load is 4500 MW. The LOLE and the reserve margin for the installed system are also known.

Table 1. Technical and Economic Data of Existing Plants

Name Fuel Type	No. of Units	Unit Capacity (MW)	F.O.R. (%)	Operating Cost ($/MWh)	Fixed O&M Cost ($/KW-Month)
Oil #1	1	200	7.0	24	2.25
Oil #2	1	200	6.8	27	2.25
Oil #3	1	150	6.0	30	2.13
LNG G/T #1	3	50	3.0	43	4.52
LNG C/C #1	1	400	10.0	38	1.63
LNG C/C #2	1	400	10.0	40	1.63
LNG C/C #3	1	450	11.0	35	2.00
Coal #1	2	250	15.0	23	6.65
Coal #2	1	500	9.0	19	2.81
Coal #3	1	500	8.5	15	2.81
Nuclear #1	1	1,000	9.0	5	4.94
Nuclear #2	1	1,000	8.8	5	4.63

The data of the existing plants installed in the network are presented in Table I. The test system includes five different GENCOs with each GENCO having the maximum construction limit of 5, 4, 3, 3 and 3 with capacities of 200, 450, 500, 1000 and 700 MW respectively for each unit [21]. The marginal costs are assumed, based on the investment cost, operation maintenance cost and salvage cost of the units. The GENCOs based on the above, calculate their total costs and select their bidding price and submit it to the ISO. The marginal costs of the five GENCOs are assumed as 4, 5, 4.5, 3.75 and 4.25, respectively based on [21]. The market constant is assumed as 9 and demand coefficient as 0.001; the market price equation is P = 9 - 0.001 x (sum of MW supplied by all GENCOs).

B. Numerical Results

There is a case study as discussed in the previous section. All constraints are taken into account. The maximum construction number of units limit is 5, 4, 3, 3, and 3 for each GENCO with individual capacities of 200, 450, 500, 1000, and 700 MW respectively. Each GENCO use different fuel such as Oil, Coal LNG, Nuclear #1, and Nuclear #2. The ISO has forecasted the total demand as 7000 MW and the minimum and maximum reserve rate as 20% to 40% respectively. The fuel mix ratio is set to be 20% for each fuel type. For the minimum reserve rate the total capacity required will be 8400 MW and for the maximum reserve rate, the total capacity required will be 9800 MW. The existing capacities are 5450 MW. Hence, the minimum and maximum capacity required will be 2950 and 4350 MW respectively [21].

The total maximum capacity available with each GENCO is 1000, 1800, 1500, 3000, and 2100 MW respectively. The total capacities produced by each GENCO at the equilibrium point were calculated by the ICA as an optimization tool.

Table 2. The Equilibrium Points Obtained by the Proposed Method Based on ICA

Equilibrium	**Player 1 (P_1)**		**Player 2 (P_2)**		**Player 3 (P_3)**		**Player 4 (P_4)**		**Player 5 (P_5)**	
1	599		23		772		1786		785	
2	817		0		553		1547		917	
3	991		0		519		1411		914	
4	1000		78		545		1357		885	
5	1000		106		573		1342		865	
6	1000		110		588		1343		854	
7	1000		107		595		1347		851	
8	1000		104		596		1349		851	
9	1000		102		595		1351		851	
10	1000		101		595		1352		851	
11	1000		101		595		1351		851	
12	1000		102		595		1351		851	
13	1000		101		595		1352		851	
14	1000		101		595		1351		851	
15	1000		101		595		1352		851	
16	1000		101		595		1352		851	
Final Solution	P_1	$Profit_1$	P_2	$Profit_2$	P_3	$Profit_3$	P_4	$Profit_4$	P_5	$Profit_5$
	1000	1101	101	10.201	595	357.595	1352	1826.552	851	724.201

The ICA method is used to find the optimal solution of each GENCO. The solution methodology is maximization the profit of each individual GENCO. This process is performed for each individual GENCO. After that this procedure is performed until the results do not change in two consecutive iterations. For this problem, there are multiple equilibrium points available.

The ICA has the capability of finding the multiple equilibrium points during different simulation runs. For the best solution the proposed algorithm, 16 different equilibrium points have been achieved. These equilibrium points along with their corresponding capacities and profits are presented in the Table II.

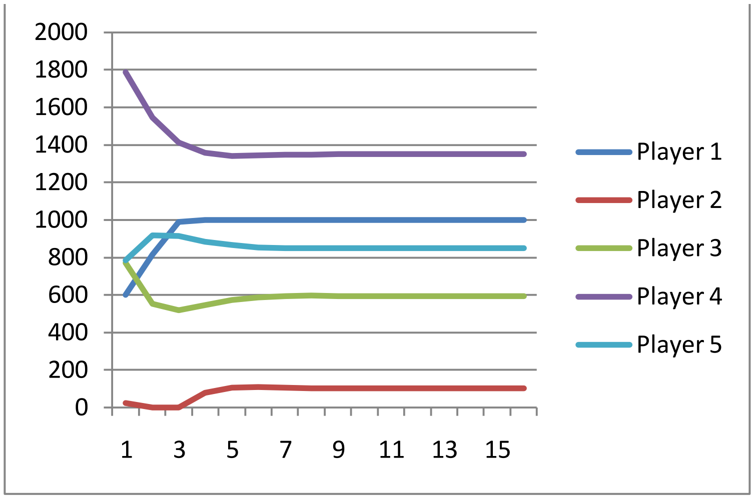

Figure 1. Fig. 1 Variation in Players' Capacity for Each Player at each Iteration

Fig. 1 shows the variation in players' capacity for each player at each iteration based on Table II. There is no variation in profit for the 5 GENCOs from iteration 15 to iteration 16 and equilibrium point is reached. A tolerance value is set so that if the difference between two iterations, for all GENCOs is less than the tolerance the procedure will terminate, otherwise it will continue.

The results obtained by the proposed method are compared with those obtained by the PSO algorithm reported in [21] in Table III.

As this table depicts the proposed method based on the ICA is more capable of finding the optimal solution of generation expansion planning rather than PSO. The total benefit of the all GENCOs by the PSO method is 3601.7 while the proposed method improved the best solution and enhanced the total benefits for more than 10% and raised it to 4019.549.

Results demonstrate the effectiveness of the proposed method. The proposed method based on ICA can guarantee the optimal solution while handle all constraints of the problem efficiently.

Table 3. Comparison of the Results Obtained by the Proposed Method Based on ICA and PSO

Benefit	**PSO [21]**		**ICA**	
	P_i	$Profit_i$	P_i	$Profit_i$
$Player_1$	1000	1035	1000	1101
$Player_2$	360	12.6	101	10.201
$Player_3$	535	286.2	595	357.595
`$Player_4$	1286	1652.5	1352	1826.552
$Player_5$	784	615.4	851	724.201
Total Benefit	3601.7		4019.549	

IV. Conclusions

This paper has addressed the competitive GEP issues. A Cournot game with Nash equilibrium has been used to model the competition between the GENCOs and gaming between the ISO and market participants in GEP problem. The GEP problem has been solved in an iterative framework by self-optimizing of each GENCO using ICA and satisfying the regulatory body in Cournot model. The results of case studies show that the proposed framework can solve the competitive GEP problem. They also show that different constraints of market can be modeled in the objective function of each GENCO or price signal of the ISO. Other signals such as incentive capacity signal can be also modeled and used in the self-optimization of each GENCO.

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