A Multi-Objective Model for Power Generation Expansion Planning

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Abstract

This paper describes and evaluates a multi-objective generation expansion model that includes aspects such as incorporation of four objectives to generate the expansion alternatives, importance given to renewable generation technologies while considering location of generation units. Using multi-criteria decision making theory, this model provides results which indicate the most recommendable amount of each type of generating technology to install at each location. A framework to solve and generate alternative solutions is provided. A case study is included to illustrate the use of the model.

Keywords
Generation expansion planning, multi-criteria optimization, Analytic Hierarchy Process

1. Introduction

The Generation Expansion Planning (GEP) Problem is defined as the problem of determining WHAT, WHEN and WHERE new generation units should be installed over a long-range planning horizon, to satisfy the expected energy demand. Since the demand is expected to increase in most cases, a small error in choosing the correct mix of generating facilities at assumed costs could result in a loss of hundred of millions of dollars, not to mention the social costs of not meeting the energy demand.

The GEP problem has been one of the most studied problems as an early application of Operations Research. An extensive set of methods have been proposed to solve the problem. Optimization methods used to solve GEP include traditional approaches such as linear, mixed-integer, non-linear and dynamic programming with decomposition schemes; metaheuristic approaches such as simulated annealing, tabu search, evolutionary algorithms, particle swarm optimization; and a combination of both. GEP keeps being a challenge for several reasons: first of all, there is uncertainty associated with the input data, such as forecasts of demand for electricity, economic and technical characteristics of new evolving generating technologies, construction lead times, and governmental regulations. A second difficulty arises as a result of considering several objectives (often conflicting) simultaneously. These objectives might include minimization of total cost, maximization of the system's reliability, and minimization of environmental effects. Usually, other costs and factors besides generation expansion costs are incorporated as constraints in the optimization problem, i.e., most GEP problems have been modeled as single-objective models which consider only the minimization of total cost. However, the least-cost expansion plan often may not be the preferred option if environmental effects are considered. With the aid of the multi-objective models, decision makers may grasp the conflicting nature and the trade-offs among the different objectives in order to select satisfactory compromise solutions for the GEP problem.

Even though powerful and attractive multi-criteria decision making analysis approaches have been developed and applied to power systems planning [1], [2], [6], [7], [12], [13], and [14], still there are areas of improvement. In some of the presented applications, the alternatives (expansion plans) are generated and in others these are known before the comparison and selection of them. The grade of detail in modeling such as the number of objectives and representation of the input data results in more detailed and more complex models. In this paper we propose a multi-objective model (MGEP) and a framework to solve the generation expansion planning problem. The main differences between MGEP and previous approaches is that the proposed MGEP model includes four objectives to generate a set of expansion alternatives, and it considers the transmission network (only in terms of the flow conservation) to analyze the geographical impact of the generation additions in order to obtain more realistic results in the electricity supply chain.

The next sections of this paper describe the model in mathematical terms, the methodology proposed, and one case study to test the performance of the proposed method. Finally, some conclusions are made from the presented material.

2. Multi-objective Generation Expansion Planning Model (MGEP)

The purpose of the MGEP model is to determine the location, type and capacity of new generation units to achieve the best compromise between different objectives, and yet meet all the operating and economic restrictions that are placed on the system. In this multi-objective model, minimization of the investment, operation and transmission costs, environmental impact, the total fuel imports and risks related to fuel price fluctuations are considered. The proposed MGEP model is a single period deterministic linear programming model which considers the current conservation Kirrchoff's laws.

In the MGEP model, the following notation is utilized: $i \in N$ is a node; $(i, j) \in A$ is an arc from node *i* to node *j*; $q \in \Theta$ is a generation unit; and $k \in F$ is a fuel type. D_i is the expected load (MW) at node *i*; I_{iq} is the investment cost ($/MW) of a unit of type *q* at node *i*; G_{iq} is the generation cost ($/MW) of a unit of type *q* at node *i* (operation & maintenance); C_{ij} is the cost ($/MW) for new transmission capacity in arc (*i*, *j*); $\bar{X}_{ij}$ is the existing (MW) capacity of transmission in arc (*i*, *j*); $\bar{G}_{iq}$ is the maximum (MW) generation capacity of units of type *q* at node *i*; $\overline{GE}_{iq}$ is the maximum (MW) generation capacity for an existing unit of type *q* at node *i*; V_k is the cost ($/units) of imported fuel of type *k*; E_q is tons of carbon dioxide emission (CO_2) per MW generated by a unit of type *q*; U_k is the domestic available amount (corresponding units) of fuel type *k*; W_q is the fuel needed (units/MW) to operate a unit of type *q*; S_k is the historical coefficient of variation in prices of fuel type *k*; and J_k is the index of units of fuel type *k*. The decision variables are: ge_{iq} is the generation (MW) from the existing units of type *q* at node *i*; gn_{iq} is the generation (MW) from new units of type *q* at node *i*; x_{ij} is flow (MW) through arc (*i*, *j*); Δ_{ij} is the additional transmission capacity (MW) in arc (*i*; *j*); and u_k is total imported fuel (units) of type *k*.

Let f_1, f_2, f_3 and f_4 be the investment & operational cost, environmental impact, imported fuel and energy price risks objectives, respectively. The MGEP model is:

min
$$f_1 = \sum_{i \in N} \sum_{q \in \Theta} \left[I_{iq}\, gn_{iq} + G_{iq} \left(ge_{iq} + gn_{iq} \right) \right] + \sum_{(i,j) \in A} C_{ij} \Delta_{ij} \qquad (1)$$

$$f_2 = \sum_{i \in N} \sum_{q \in \Theta} E_q \left(ge_{iq} + gn_{iq} \right) \qquad (2)$$

$$f_3 = \sum_{k \in F} V_k u_k \qquad (3)$$

$$f_4 = \sum_{k \in F} S_k \sum_{i \in N} \sum_{q \in \Theta} \left(ge_{iq} + gn_{iq} \right) \qquad (4)$$

Subject to

$$\sum_{(j,i) \in A} x_{ji} - \sum_{(i,j) \in A} x_{ij} + \sum_{q \in \Theta} \left[ge_{iq} + gn_{iq} \right] = D_i \qquad i \in N \qquad (5)$$

$$x_{ij} - \Delta_{ij} \leq \bar{X}_{ij} \qquad (i, j) \in A \qquad (6)$$

$$ge_{iq} \leq \overline{GE}_{iq} \qquad i \in N, q \in \Theta \qquad (7)$$

$$gn_{iq} \leq \bar{G}_{iq} \qquad i \in N, q \in \Theta \qquad (8)$$

$$\sum_{i \in N} \sum_{q \in J_k} W_q \left[ge_{iq} + gn_{iq} \right] - u_k \leq U_k \qquad k \in F \qquad (9)$$

$$ge_{iq}, gn_{iq}, \Delta_{ij}, x_{ij}, u_k \geq 0 \qquad (10)$$

In this mathematical program, equation (5) is the node balance constraint; (6) puts transmission capacity limits on each arc (i, j); (7) and (8) limits the generation capacity for each unit type q in node i; (9) constrains the fuel demand for each fuel type k by fuel either from local markets, or imported fuel. The model is a multiobjective linear programming problem with $2|N||\Theta|(|A|+2|F|)$ variables and $(|N|+|A|+|F|)2|\Theta||N|$ constraints.

3. Framework to solve MGEP

The proposed solution approach of this model consists of two phases. In the first phase a set of non-dominated solutions (expansion plans) are found using four multi-criteria programming methods: max-min, min-max, compromise programming, and weighting approach [8]. These methods do not require any preference information from the decision maker (DM). For the second phase, the non-dominated solutions are rank-ordered by using the Analytic Hierarchy Process (AHP) [10]. In the max-min solution, decision maker (DM) is very pessimistic in outlook and wants to maximize over the decision alternatives the achievement in the weakest criterion for each individual alternative (solution) whereas in min-max, the DM wants to minimize the maximum opportunity loss (the difference between the ideal solution of a criterion and the achieved value of that criterion in an alternative). Compromise programming identifies the preferred solution that is as close to the ideal solution as possible. The ideal and anti-ideal solutions, which are not feasible solutions, are the upper and lower bound of the criteria set.

3.1 Phase One

1. After finding the ideal and anti-ideal solutions for the MGEP problem, three non-dominated solutions (A_1, A_2, A_3) are found using the min-max, max-min, and compromise programming methods, respectively.
2. By generating a large number (N) of random sets of weights for each criterion, N normalized single-objective GEP problems are solved. The large number of cases gives the opportunity to explore widely the feasible region of non-dominated solutions for the problem.
3. The K-means cluster algorithm is used to obtain K clusters (K non-dominated solutions) based on the cost criterion f_1 from the N solutions generated in step 2.
4. A total of $K+3 = m$ possible non-dominated solutions or expansion alternatives are obtained from this phase. These alternatives are the inputs for completing the second phase.

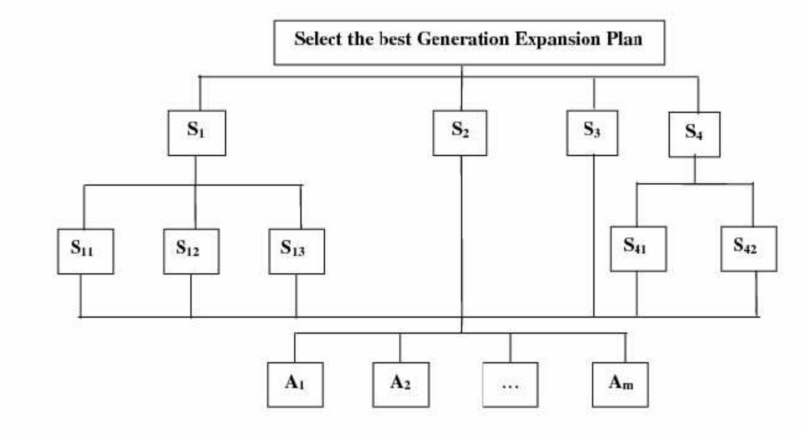

Figure 1: AHP Hierarchy

3.2 Phase Two

1. Use AHP to select the best or more attractive alternative from the set of alternatives generated in phase one. The hierarchy classification of criteria is presented in Figure 1. In Figure 1, A_i is the i^{th} alternative expansion plan found in the phase one. There are four criteria in the first level S_i. The first criterion S_1, is cost ($) which contains the three sub-criteria: investment S_{11}, operation S_{12} and transmission S_{13}. The second criterion S_2, is environmental impact (tons of CO_2). S_2 can also include SO_2 and NO_x. The third criterion S_3, is outsourced fuel ($). Finally, the fourth criterion S_4 is risk, which includes risk of fossil-fuel price fluctuations S_{41} ($) and nuclear risk S_{41} (MW).
2. The pairwise judgments comparisons between criteria and sub-criteria are given by the DM.
3. Obtain the priority for each one of the alternatives considered.
4. The alternatives are ranked and the best is identified from the ranking.

4. Illustrative Example

The proposed methodology will be illustrated using the Interconnected Grid Mexican Power System (IRMES) at the level of regions. In IRMES, there are 26 nodes (regions), 37 arcs, 8 types of generation units, and four types of fuel. Generation technology options for capacity additions include: conventional steam units, coal units, combined cycle modules (CC), nuclear, gas turbines (TG), wind farms, geothermal and hydro units. The types of non-renewable fuel are: coal, gas, oil and uranium. Some of the needed input data was taken from [11], and the rest was estimated using different sources [4]. The base year is 2004, and the planning horizon consists of 10 years; the existing capacity in the system is 41443 MW and the expected demand in 2015 is 54670 MW. For this system, the resulting MGEP model has 2*26*8 + 2*37 + 4 = 494 variables, and 26+ 37 + 4 = 67 constraints.

GAMS code was used to generate the expansion alternatives in the first phase of the proposed methodology. A total of 2000 scaled single-objective problems were solved using randomly generated set of weights for each criterion. Those 2000 non-dominated solutions were filtered to 8 alternatives (clusters) using the K-means algorithm. The obtained alternatives besides the min-max and compromise programming non-dominated solutions represent a total of 10 non-dominated solutions (see Table 1) which are the base for the second phase of the proposed methodology (select the most attractive expansion plan). In the case study, the max-min solution coincided with the min-max solution, therefore only one of them is reported. As shown in Table 1, each alternative (non-dominated solution) is between the ideal and anti-ideal values, and diversity exists among them.

Table 1: Resulting Pay-off table

	weights				S_1	S_2	S_3	S_4
Alternative	w_1	w_2	w_3	w_4	Cost	Environment	Fuel	Risk Prices
A_1	min-max				1.75E+10	21929.89	155.65	81544.64
A_2	compromise programming				2.35E+10	19294	2786.18	66646.91
A_3	0.45	0.06	0.45	0.04	1.20E+10	26452.15	74382.87	111101.58
A_4	0.28	0.08	0.51	0.12	1.57E+10	22945.43	0	87411.45
A_5	0.37	0.08	0.15	0.40	1.82E+10	21715.9	2786.18	79150.48
A_6	0.41	0.29	0.11	0.19	1.92E+10	21118.27	155.65	77736.23
A_7	0.34	0.13	0.22	0.31	1.70E+10	22214.3	155.65	82504.83
A_8	0.08	0.43	0.40	0.09	2.39E+10	19214.49	2786.18	66773.36
A_9	0.07	0.06	0.40	0.47	2.37E+10	19644.25	10500	64819.59
A_{10}	0.04	0.16	0.40	0.40	2.39E+10	19591.92	2786.18	64804.21
ideal					1.20E+10	19214.49	0	63891.4
anti-ideal					3.37E+10	29844.5	8089772.89	140232.86

With respect to the second phase of the proposed methodology, the payoff table for the second level (sub-criteria) in the AHP hierarchy is presented in Table 2. Continuing with the second phase of the methodology, based on the scale proposed in [10], we as DM define the following pairwise judgment matrix for the first level of the AHP hierarchy (Table 3). Also, the pairwise judgment matrices for the second level of the hierarchy are presented in Table 4 and Table 5. It is important to mention that these matrices can be different for another DM, thus obtaining different conclusions.

Table 2: Resulting Pay-off table for subcriteria

	S_{11}	S_{12}	S_{13}	S_{42}
Alternative	Investment	Operation	Transmission	Nuclear Risk
A_1	1.64E+10	1.15E+09	179234.3	5550.4
A_2	2.24E+10	1.19E+09	211348.76	6413.8
A_3	1.10E+10	1.05E+09	183047.07	3367.8
A_4	1.46E+10	1.14E+09	233941.48	5522.74
A_5	1.71E+10	1.17E+09	221646	6413.8
A_6	1.81E+10	1.16E+09	218986.3	5550.4

A_7	1.58E+10	1.15E+09	194729.94	5550.4
A_8	2.27E+10	1.19E+09	203926.62	6413.8
A_9	2.25E+10	1.21E+09	220061.61	6413.8
A_{10}	2.27E+10	1.21E+09	361184.03	6413.8

Table 3: Judgment Matrix

	S_1	S_2	S_3	S_4
S_1	1	1/3	1	1
S_2	3	1	2	1
S_3	1	1/2	1	1/3
S_4	1	1	3	1

a. Judgment Criteria Matrix

	S_{11}	S_{12}	S_{13}
S_{11}	1	3	1
S_{12}	1/3	1	1
S_{13}	1	1	1

b. Judgment Cost Criteria Matrix

	S_{41}	S_{42}
S_{41}	1	2
S_{42}	½	1

c. Judgment Risk Criteria Matrix

Based on the defined judgments and following the AHP calculations procedure, the ranking for each alternative is: $A_4 > A_3 > A_1 > A_7 > A_6 > A_8 > A_9 > A_2 > A_5 > A_{10}$. The best expansion alternative is A_4, followed by A_3 and A_1 (min-max). Alternative A_4 is better by a significant amount since this is the only alternative that does not require import of fuel. Also, A_3 is the one who has the minimum total cost (see Table 1). A_1 is an attractive option for expansion that does not require any weights definition; and A_7 is also another interesting alternative to analyze. The composition of technologies installed by alternative A_4 can be observed in Figure 2.

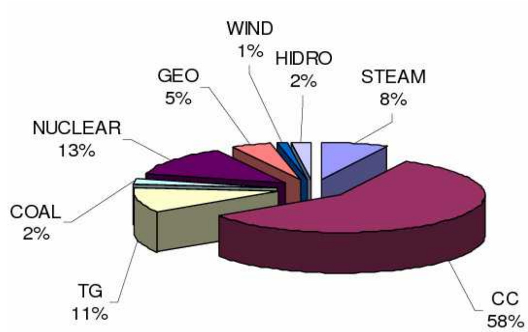

Figure 2: Expansion Plan by *A_4*

5. Conclusion

A single-period multi-objective model (MGEP) has been proposed in this paper which considers aspects that previous models have not included. The incorporation of more than three criteria to generate the expansion alternatives, the importance given to renewable generation technologies, and the geographical location of the new generation units are some features of the MGEP which have not been considered simultaneously in the literature.

Although the solutions obtained with MGEP can be considered as approximations to the real generation expansion planning problem (integer investment variables, multi-period model, and with the two Kirrchoff's laws), they look reasonable when compared with the Mexican government's expansion plan [11]. In addition, the computational effort to obtain them is low; with more accurate input data, the results can be better. Nowadays, the expansion planning of electric power systems is usually done by using sophisticated and costly computational tools [3, 5]. However, with MGEP good and very fast mix additions results can be obtained for the problem.

There are also some drawbacks for the MGEP which can serve to define future research. Including more objectives, considering uncertainty into the problem, solving a multi-period model and a better representation of the decision variables in MGEP are four possible extensions to the model. However, the more objectives in a multi-criteria problem implies a more complex problem. The additional objectives require more computational effort to generate the expansion alternatives (nondominated solutions).

In addition, there have been few applications of interactive methods to MGEP problems. A major obstacle is time: access to key decision makers is limited and it could be costly. A second obstacle is that there is relatively little experience with such methods in a group setting, where group members have very different priorities. Applications investigating these issues are needed. Another alternative to solve multi-objective optimization problems is evolutionary algorithms. Solving optimization problems with multiple and conflicting objectives is generally considered as a difficult task. This is why the evolutionary algorithms have been extended from single objective problems to multiple objectives during the past two decades.

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