A FUZZY APPROACH TO THE GENERATION EXPANSION PLANNING PROBLEM IN A MULTI-OBJECTIVE ENVIRONMENT

by

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In many power system problems, the use of optimization techniques has proved inductive to reducing the costs and losses of the system. A fuzzy multi-objective decision is used for solving power system problems. One of the most important issues in the field of power system engineering is the generation expansion planning problem. In this paper, we use the concepts of membership functions to define a fuzzy decision model for generating an optimal solution for this problem. Solutions obtained by the fuzzy decision theory are always efficient and constitute the best compromise.

Key words: generation expansion planning, fuzzy decision theory, multi-objective decision

INTRODUCTION

Electricity is the basic form of energy in modern societies and the demand for it has been increasing year after year. A widespread use of various advanced electronic apparatus intensifies the sheer need for high quality electric energy. Generation facilities of a power system must be expanded if it is to be able to meet future demand increase. Hence, the generation expansion planning (GEP) problem is perceived to be an important issue in the field of power system engineering. GEP concerns the problem of when and where to build new power plants to meet future energy demand and to minimize the sum of fixed and variable costs of generation facilities.

GEP has been formulated as a non-integer programming problem in which a continuous variable is allocated to each type of generating units [1-3]. One possible approach is to apply linear programming after linearizing the original problem [4]. Generally, the proposed approach is based on non-linear programming [5].

GEP may be formulated as a multi-objective optimization problem in which the economy, system security, and environmental stress should be simultaneously taken into account. GEP has to cover a long time span, well exceeding a decade or two. This means that it should include assumptions which hardly change or are liable to uncertainties during the planning period. In reality, planning engineers must make up many alternative plans to allow for these uncertainties and future fluctuations of basic parameters such as fuel costs and demand forecasts. The decision maker (DM) must select between these alternative plans. Thus, the incorporation of uncertainties has been the recent trend in GEP [6].

The solutions to the multi-objective optimization problems are the Pareto solutions which consist of uncountable solution points. The DM must decide/select one out of the countless solutions possible by considering various factors relating to the planning in question.

Bellman and Zadeh [7] and Esogbue and Bellman [8] deal with decision-making in a fuzzy environment. They consider fuzzy objectives and fuzzy constraints as fuzzy sets in the realm of alternatives. Zimmerman [9] deals with the fuzzy approach for solving linear programming with multi-objective functions. He shows that solutions obtained by the fuzzy approach are always efficient ones. He also

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demonstrates the consequence of using different ways of combining individual objective functions in order to determine an optimal compromise solution.

The structure of this paper is as follows: in the next section we formulate the GEP as a linear programming problem and afterwards we use the concepts of membership functions to determine an optimal compromise solution to our problem. Then, an illustrative numerical test is provided to demonstrate the efficiency of our proposed approach; finally, we list the conclusions reached.

THE FORMULATION OF THE GEP PROBLEM

The fuzzy, multicriteria-planning problem was first formulated by Slowinski [10] for a water distribution system. Teghem and Kunsch [11] presented an interactive, stochastic multiobjective-analysis of a small power system using a linear programming package. Miranda and Matos [12] presented the basic concepts and tools to model the uncertainty in electric distribution systems with fuzzy sets, while Mohammadi *et al.* [13] presented a fuzzy-decision making procedure for engineering electric power distribution scheduling. Ponce de Leao and Matos [14] conceptualized the electric distribution problem as a fuzzy multiobjective problem, while Kagan and Adams [15] extended Slowinski's procedure [10] to the electric distribution system. Miranda *et al.* [16] proposed an approach based on genetic algorithms for the fuzzy multi-stage problem.

The fuzzy set theory seems to be a natural setting for such multiobjective problems. According to the work of Hiroshi Sasaki and Junji Kubokawa [17], the GEP problem can be defined as a problem of generation technologies and transmission networks to be installed to support power exchange between areas. They assumed the following:

(1) fuel cost is the same among areas under consideration, that is, the cost is the same for the same kind of generation technology,
(2) each unit has no time delay in its start-up and shutdown,
(3) each unit can be operated without any fault,
(4) priority order in the start-up process is predetermined,
(5) load duration curve, maximum demand and spinning reserve are given, and
(6) the load duration curve, which is the same for all areas, is assumed to consist of five levels, as shown in fig. 1.

The last assumption is necessary if the problem is to be solved by linear programming. Symbols *m*, *i*, and *k* denote the load level, area, and kind of generation technology, respectively. The set of constraints and objective functions are explained in the following two subsections.

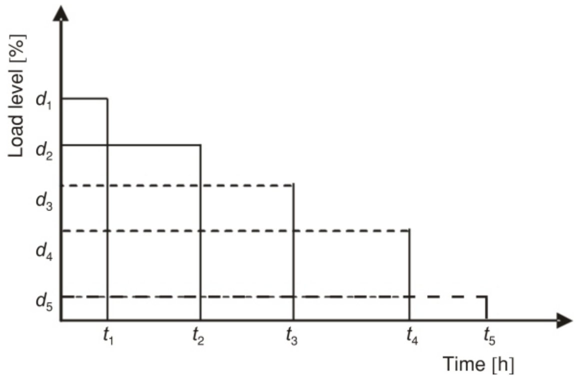

Figure 1. Approximated load during curve

Constraints

We have many types of constraints, such as constraints on the generation capacity, on the output share of each generation technology, on the output of each generation technology, power exchange, capacity of a new installation and, finally, constraints on the lower and upper limits of the fluctuation in a forecasted load.

Constraints on generation capacity

This has to do with the maximum generation capacity of the total system relative to the maximum load demand and may be expressed by

$$_{i\ k}(x_{ik} \quad \Delta x_{ik}) \quad (1 \quad r) \ _{i}(D_i \quad \Delta D_i) \qquad (1)$$

where x_{ik} is the capacity of the existing technology *k* in area *i*, Δx_{ik} – the capacity of a newly installed technology *k* in area *i*, D_i – the minimum forecasted load demand in area *i*, ΔD_i – the change in the forecasted load demand in area *i*, and *r* – the reserve rate.

Constraints on the output share of each generation technology

The sum of the output of each generation technology must be equal to the sum of power exchange load demand at each load level

$$_{k} Y_{mik} \quad _{ij}(L_{mij} \quad \Delta L_{mij}) \quad d_{mi} \quad \Delta d_{mi}$$
$$L_{mij} \qquad L_{mji} \qquad (2)$$

where Y_{mik} is the generation share of technology *k* at load level *m* in area *i*, L_{mij} – the power exchange between areas *i* and *j* through the existing transmission line at load level *m*, ΔL_{mij} – the power exchange between areas *i* and *j* through the new transmission line at load level *m*, d_{mi} – the forecasted load demand in area i at load level *m*, and Δd_{mi} – the change in forecasted load demand at load level *m* in area *i*.

Constraints on the output of each generation technology

At each load level, the output of each generation cannot exceed its installation capacity

$$_{i} Y_{mik} \quad _{i} (x_{ik} \quad \Delta x_{ik}) \qquad (3)$$

Constraints on power exchange

The amount of power exchange between two areas must not exceed the transmission capacity of the transmission line

$$\left|L_{mij}\right| \quad L_{ij}; \quad \left|\Delta L_{mij}\right| \quad \Delta L_{ij} \qquad (4)$$

where L_{ij} is the transmission capacity of the existing line between areas *i* and *j*, and ΔL_{ij} – the transmission capacity of the new line between areas *i* and *j*.

Constraints on the capacity of a new installation

There are certain constraints on the capacity of a newly installed generation technology and transmission lines. This is clear in the case of nuclear plants. Since any nuclear unit is operated at a constraint output, it cannot follow up load variations, *i. e.* the maximum total capacity of nuclear units should be prescribed so that they could be used as base loading

$$\underline{\Delta X_{ik}} \quad \Delta X_{ik} \quad \overline{\Delta X_{ik}}; \ \Delta L_{ij} \quad \overline{\Delta L_{ij}} \qquad (5)$$

where $\underline{\Delta X_{ik}}$ and $\overline{\Delta X_{ik}}$ are the lower and upper limits of a new installation of technology *k* in area *i*, respectively, and $\overline{\Delta L_{ij}}$ – the upper limit of capacity of a new transmission line between areas *i* and *j*.

Lower and upper limits of fluctuations in a forecasted load

The fluctuations between the actual load demand and the forecasted one during a planning period may lie in a range

$$\underline{\Delta D_i} \quad \Delta D_i \quad \overline{\Delta D_i} \qquad (6)$$

where $\underline{\Delta D_i}$ and $\overline{\Delta D_i}$ are the lower and upper limits of fluctuations in a demand forecast, respectively.

Objective functions

According to the model of Hiroshi Sasaki and Junji Kubokawa [17], we shall take into consideration the three objective functions of the GEP problem, that is, economy, supply reliability, and environmental impact, assuming that all the variables can assume continuous values. For the objective of supply reliability, the reserve rate of about 6-10% of its peak demand is assumed so as to accommodate for unforeseen faults or sudden loss of generation.

Economic objective function (to be minimized)

For this objective, the sum of annual investment costs of generation plants, transmission lines, fuel costs and purchase costs through interchange is considered. It is assumed that investment costs are in proportion to its capacity and fuel costs to the amount of electric energy product. The cost of power purchase is assumed to be proportional to the capacity of the inter-tie transmission line. The economic objective is expressed as

$$Z_1 \quad _{i}\ _{k} f_{ik} \Delta x_{ik} R \quad _{m}\ _{i}\ _{k} \nu_k Y_{mik} T_m R$$
$$_{i}\ _{j} c_{ij} \Delta L_{ij} R \quad _{m}\ _{i}\ _{j} b_{ij} (\Delta L_{mij} \quad L_{mij}) T_m R \qquad (7)$$

where f_{ik} is the annual investment costs of generation technology *k* in area *i* per unit, *R* – the conversion coefficient to the present worth, ν_k – the fuel costs of generation technology *k*, T_m – the duration of load at level *m*, c_{ij} – the annual investment costs of transmission lines between areas *i* and *j* per unit, and b_{ij} – the annual costs of power exchange between areas *i* and *j* per unit.

Environmental objective function (to be minimized)

Although thermal plants emit NO_x, SO_x, as well as CO_2, only CO_2 will be taken into consideration for the sake of simplicity. The amount of CO_2 emission is assumed to be in proportion to the generated energy and expressed by

$$Z_2 \quad _{m}\ _{i}\ _{k} e_k Y_{mik} T_m R \qquad (8)$$

where e_k denotes the emission coefficient of CO_2 of technology *k*.

Supply reserve margin objective function

This objective reflects fluctuations in the load forecast and should be maximized to keep high supply reliability. The sum of fluctuations in load demand in all areas is to be considered and this objective expressed as

$$Z_3 \quad _{i} \Delta D_i \qquad (9)$$

THE FUZZY DECISION APPROACH

In what follows we will restrict our consideration to determining the optimal compromise solutions to our problem. The fuzzy approach is used for determining possible solutions. In proposed model, as opposed to the approach given in reference [17], we will formulate the problem in a fuzzy version by fuzzificating all objective functions (7), (8), and (9). This approach has the following advantages:

(1) the problem is simplified and the representation more realistic and practical, this is because we are dealing with a fuzzy, not a well defined problem as it is, and

(2) the use of membership functions to represent the goals of the DM offers exceptional flexibility for the decisions proposed.

According to Zimmermann's approach [9], the linear membership functions for the objectives: min Z_1, min Z_2, and max Z_3 are redefined, respectively, as follows

$$\mu_{Z_1} \quad \begin{matrix} 1, & Z_1 \quad Z_1 \\ \dfrac{\overline{Z}_1 \quad Z_1}{\underline{Z}_1 \quad \overline{Z}_1} & \underline{Z}_1 \quad Z_1 \quad \overline{Z}_1 \\ 0 & Z_1 \quad \overline{Z}_1 \end{matrix}$$

$$\mu_{Z_2} \quad \begin{matrix} 1 & Z_2 \quad \underline{Z}_2 \\ \dfrac{\overline{Z}_2 \quad Z_2}{\underline{Z}_2 \quad \overline{Z}_2} & \underline{Z}_2 \quad Z_2 \quad \overline{Z}_2 \\ 0 & Z_2 \quad \overline{Z}_2 \end{matrix}$$

and

$$\mu_{Z_3} \quad \begin{matrix} 1 & Z_3 \quad \overline{Z}_3, \\ \dfrac{Z_3 \quad \underline{Z}_3}{\overline{Z}_3 \quad \underline{Z}_3} & \underline{Z}_3 \quad Z_3 \quad \overline{Z}_3, \\ 0 & Z_3 \quad \underline{Z}_3 \end{matrix}$$

where $\underline{Z}_1 \quad \min Z_1$, $\underline{Z}_2 \quad \min Z_2$, $\underline{Z}_3 \quad \min Z_3$, $\overline{Z}_1 \quad \max Z_1$, $\overline{Z}_2 \quad \max Z_2$, and $\overline{Z}_3 \quad \max Z_3$.

The problem now is how to aggregate the objective functions into the fuzzy state. An extended concept of Bellman and Zadeh [7] and Zimmermann [9] posed two aggregate operators, the min operator, a non-compensatory operator, and the product operator, a compensatory one. However, the problem resulting from using a product operator is non-linear and generally difficult to solve. Thus, the product operator is seldom used. Therefore, the conjunction and/or the min operator must be used, giving

$$\lambda \quad \min(\mu_{Z_1}, \mu_{Z_2}, \mu_{Z3}) \tag{10}$$

where λ is the final membership function. The min operator can be replaced by inequality and in addition, we would like to obtain the maximum value of λ. Thus, the final programming problem is obtained from the above equation as

$$\max \lambda \tag{11}$$

subject to

$$\lambda_1 \quad \frac{\overline{Z}_1 \quad Z_1}{\underline{Z}_1 \quad \overline{Z}_1}, \quad \lambda_2 \quad \frac{\overline{Z}_2 \quad Z_2}{\underline{Z}_2 \quad \overline{Z}_2}, \quad \lambda_3 \quad \frac{Z_3 \quad Z_3}{\overline{Z}_3 \quad \underline{Z}_3}$$

Set of constraints (1-6)

The disadvantage of (10) or (11) is due to the non-compensatory nature of the min operator. To overcome this difficulty, a compensatory operator may be used. Lee and Li [18] proposed the use of an arithmetical average operator and then our problem becomes

$$\max \beta \quad \frac{1}{3}(\lambda_1 \quad \lambda_2 \quad \lambda_3) \tag{12}$$

subject to

$$\lambda_1 \quad \frac{\overline{Z}_1 \quad Z_1}{\underline{Z}_1 \quad \overline{Z}_1}, \quad \lambda_2 \quad \frac{\overline{Z}_2 \quad Z_2}{\underline{Z}_2 \quad \overline{Z}_2}, \quad \lambda_3 \quad \frac{Z_3 \quad \underline{Z}_3}{\overline{Z}_3 \quad \underline{Z}_3}$$

Set of constraints (1-6).

Even with the compensatory operator, the results are unbalanced. In order to balance them, Lee and Li [18] proposed the addition of a second phase of their procedure by using the numerical results of the first phase. Assuming the solution obtained for the first is $(\lambda_1^*, \lambda_2^*, \lambda_3^*)$, the second phase is formulated as

$$\max \beta \quad \frac{1}{3}(\lambda_1 \quad \lambda_2 \quad \lambda_3) \tag{13}$$

subject to

$$\lambda_1^* \quad \lambda_1 \quad \frac{\overline{Z}_1 \quad Z_1}{\underline{Z}_1 \quad \overline{Z}_1}, \quad \lambda_2^* \quad \lambda_2 \quad \frac{\overline{Z}_2 \quad Z_2}{\underline{Z}_2 \quad \overline{Z}_2},$$

$$\lambda_3^* \quad \lambda_3 \quad \frac{Z_3 \quad \underline{Z}_3}{\overline{Z}_3 \quad \underline{Z}_3}$$

Set of constraints (1-6).

NUMERICAL TEST SYSTEM

For the sake of clarity, the proposed fuzzy approach is tested by the following system. Four kinds of generation sources are considered: wind (*e.g.* Al-Zaafrana Plant), water (*e. g.* High Dam), oil (*e. g.* Assuit Plant), and liquefied natural gas (LNG) (*e. g.* North Cairo Plant).

Four areas and a period of planning of 10 years were taken into consideration. Figure 2 shows this system where generating plants and transmission lines depicted in doted lines signify future possible installations, while existing plants are depicted in solid lines. Open circles represent the generation possibility distribution of the generators and arrows represent the load possibility distribution at that area. Conversion coefficient from oil to LNG is 1.183 and we have two load levels of 14600 and 13850 MW. Load demands in the reference year and demand forecasts in the target year in each area are given in tab. 1.

We solved problem (12) and got the values λ_1^*, λ_2^*, and λ_3^* of and then solved problem (13). For solving problems (12) and (13), we used the WinQSB software which uses the branch and bound method. Figures 3-5 show that the values of objective functions

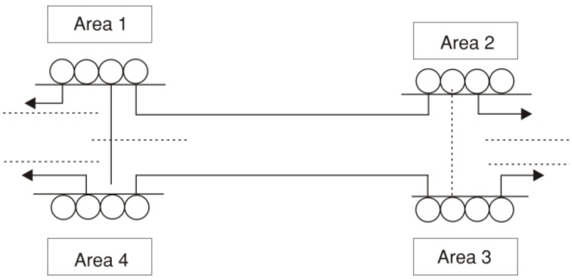

Figure 2. Test system

Table 1. Load demand in each area

Area	Load demand in the reference year [MW]	Forecasted load demand in the target year [MW]
1	1000	1300
2	2200	3400
3	3200	4200
4	3000	3800

are optimal in the case of fuzzificating. In fig. 5, the cost in the crisp case is clearly the optimum value, occurring when there was no fluctuation.

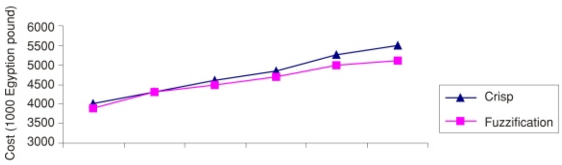

Figure 3. The cost in case of fuzzy and crisp economy objective function

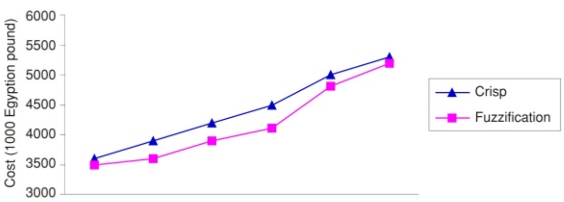

Figure 4. The cost in case of fuzzy and crisp environment objective

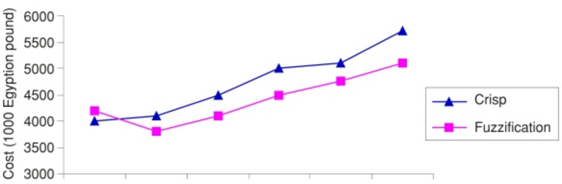

Figure 5. The cost in case of fuzzy and crisp supply reserve margin objective function

We show that the obtained fuzzy solution seems to be more realistic and efficient than other solutions obtained by deterministic studies, as given in reference [7]. From figs. 3-5, we can determine that our proposed approach reduces the total cost by 4.93%.

CONCLUSION

Using the concept of membership functions, this paper presented a fuzzy approach to the GEP problem in a multi-objective environment. The theory of fuzzy sets has been employed to formulate and solve the GEP problem. In our proposed model, we formulated the problem in a fuzzy version by fuzzificating all objective functions. The novelties of our approach have mainly to do with the use of membership functions for each objective function. In the proposed fuzzy approach, it is possible to make a trade-off between the three objectives. This can, therefore, be useful for the decision maker. An illustrative numerical test has been given to demonstrate the efficiency of the proposed approach. The solution obtained by a fuzzy multi-objective decision was always efficient and constituted the best compromise. Our proposed approach reduces the total cost by 4.93%.

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ФАЗИ ПОСТУПАК ПЛАНИРАЊА РАЗВОЈА ЕНЕРГЕТИКЕ У ВИШЕЦИЉНИМ ОКОЛНОСТИМА

У многим проблемима енергетских система показало се да коришћење оптимизационих техника претходи смањењу трошкова и губитака система. Тако се и вишециљно фази одлучивање користи за решавање проблема енергетских система. Једно од најзначајнијих питања у области енергетског инжењеринга јесте задатак планирања пораста производње енергије. У раду се користи концепт функције припадности да се дефинише модел фази одлучивања за генерисање оптималног решења овог задатка. Решења добијена теоријом фази одлучивања увек су успешна и најбоље усаглашена.

Кључне речи: планирање развоја енергетике, фази теорија, вишециљно одлучивање