Environmental economic dispatch with fuzzy and possibilistic entities

Despacho económico ambiental con variables difusas y posibilitas

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Abstract

In this paper a fuzzy possibilistic model for Environmental Economic Dispatch is presented, in order to consider adequately some involved uncertain variables. The developed model can be viewed as an integrative focus where uncertainty is not considered like a simple decision making parameter but it is analyzed as a criterion decision. Here, a fuzzy possibilistic model looks for reflecting the imprecision, ambiguity, and vagueness present in the analyzed problem. Fuzzy sets and possibility theory are an alternative to do this, because they allow including this sort of imperfect information into the problem.

------ *Keywords:* Decision-Making, Environmental, Economic Dispatch, Fuzzy sets, Possibility theory

Resumen

En este documento se presenta un modelo difuso posibilista para el problema del Despacho Económico Medioambiental con el propósito de considerar adecuadamente algunas formas de incertidumbre. El modelo desarrollado puede ser visto como un enfoque integrador, donde la incertidumbre se considera no solo como un simple parámetro en la toma de decisiones, sino fundamentalmente como un criterio de decisión. El modelo propuesto busca presentar adecuadamente la imprecisión, la ambigüedad, y la vaguedad presente en el problema analizado sobre todo la proveniente de la variable ambiental. Los conjuntos difusos y la teoría de posibilidad son una alternativa

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para lograr este propósito, porque permiten incluir esta clase de información imperfecta en el problema.

------ *Palabras clave*: Despacho económico, medio ambiente, conjuntos difusos, teoría de posibilidad, toma de decisión

Introduction

As the principles of free market have been applied to the power system, an increasing emphasis in development and utilization of optimization tools (decision tools) have occurred which on the one hand, should model the power system elements appropriately, and also, consider the planner's needs adequately, in relation to the problem representation and the interpretation of solution. Inside these tools, the economic dispatch (ED) is found, which in the two last decades has received a lot of attention. This tool has particular interest for the electric generation companies and systems operators, which regard it as one of their more important needs for activities of operation and planning.

Economic dispatch is the economic optimization process that determines a combination of generators and levels of electricity output to meet demand at the lowest cost, given the operational constraints of the generation fleet and the transmission system. Such as constraints are represented by a set of equality and inequality restrictions that are satisfied by means of adjustment of the control variables of power system. The equality restrictions are the equations of active and reactive power flow at each bus, and the inequality restrictions are the limits that exist on the control variables, in addition to the operating limits of the dependent variables of the power system. On the other hand, nowadays there is a growing recognition that the current growth of human activity cannot continue without significantly affecting the environmental quality. Then, new instruments are required to handle sustainability issues in different areas of human activity.

All over the world, electricity remains to be a fundamental element of national development. Obviously, energy production and consumption is connected to environmental pressure in many aspects. Particularly, environmental damage of power generation can be quite significant. In electricity generation, the emissions, discharges, and other effects of power production affect the health of nearby and sometimes distant populations, as well as the natural environment. Although these impacts have a direct bearing on individuals' well-being, the impacts are not usually factored into any of the decisions to generate or consume electric power [1]. Additionally, the increase of electrical demand raises concerns about the environment ability to sustain this development without harm to itself; therefore, it is indispensable to develop adequate decision-making tools in order to face the environmental problems from the perspective of power systems [2, 3].

When the environmental variable is included in economic dispatch, it is necessary to deeply analyze the attached characteristics and uncertainty of this variable, and consequently, to examine the current mechanisms for dealing with environmental issues. As a consequence of previous analysis, the necessity for alternative focuses as well as the use of nontraditional techniques which could strengthen the decision-making process will be justified. In this context, structures like: multi-criteria paradigm, fuzzy logic and possibility theory are proposed as tools which provide a greater quantity of information for a better decision-making [4].

The traditional ED basically characterizes for two fundamental aspects:

- It is problem of great dimension, strongly restricted, nonlinear and nonconvex.
- The limited and vague knowledge on the performance of power system conform these have evolved.

When environmental criterion is included in ED, both features are accentuated.

The first limitation is managed through numerical optimization procedures based on the successive linearization, specifically, the first and second derivate of the objective function and its restrictions, that are used as a direction search (steepest descent method), or by methods of linear programming for imprecise models. The advantages of such methods are found in their mathematical bases. The second limitation, related with the incomplete knowledge of the problem, preclude the reliable use of expert systems where structuring a complete, coherent and closed system of rules, is not possible. Therefore it is necessary to make use of adequate mathematical foundations for the development of appropriate tools which allow not only modeling such aspects but besides, interpreting in that context the obtained solutions. This article seeks to contribute in this second limitation to the improvement of ED solution when an environmental criterion is added.

Methodology

Traditional formulation

Mathematically, the traditional ED is shown in (1) as follow:

$$\begin{aligned} &Minimize\ \ F(x,u) \\ &subject\ to\ \ h_i(x,u)=0 \quad i=1....n\ (equality\ constrains) \\ &\qquad\qquad g_j(x,u)\le 0 \quad j=1....m\ (inequality\ constrains) \end{aligned} \quad (1)$$

Where x is the vector of control variables (the generator active powers, the generator bus voltages, the transformer tap settings, and the reactive power of switchable VAR sources); and, u is the vector of dependent variables (slack bus power, load bus voltages, generator reactive power outputs, and transmission line flows). Additionally, it is necessary to consider a set of non control variables such as active and reactive power demand of load bus.

Generally in the ED, the objective function is minimization of total cost of the active power as shown in (2). It is assumed that individual costs of each generator are only dependent on the generated active power, and that is represented by second-rate curves. The objective function for the entire system can be written as the sum of quadratic costs of each generator, that way:

$$F=\sum_{i=1}^{NG} a_i + b_i * Pg_i + c_i * Pg_i^{\ 2} \quad (2)$$

Where NG is the number of generators included the slack generator. Pg_i is the active generation of the ith generator; and a_i, b_i, c_i are the coefficients of the cost curves of ith generator. While the objective function is minimized, it is necessary to insure that the total generation should satisfy the demand system plus the losses on transmission lines. The power flow equations are defined in (3)

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix} = \begin{bmatrix} P_k(V,\theta)-(Pg_k - Pd_k) \\ Q_k(V,\theta)-(Qg_k - Qd_k) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (3)$$

With k=1…NB

Where NB is the number of system buses, Pd_k and Qd_k are active and reactive demand of load bus respectively, and the net injections in the bus k of active and reactive power, Pk and Qk, are defined in (4):

$$\begin{aligned} P_k(V,\theta) &= \sum_{m=1}^{NB} V_k V_m (g_{km}\cos(\theta_{km}) + b_{km}\sin(\theta_{km})) \\ Q_k(V,\theta) &= \sum_{m=1}^{NB} V_k V_m (g_{km}\sin(\theta_{km}) + b_{km}\cos(\theta_{km})) \end{aligned} \quad (4)$$

Where V_k is the voltage magnitude of bus k, θ_k the voltage phase of bus k, g_{km} and b_{km} are the conductance and susceptance of the line between buses k y m, and $\theta_{km}=\theta_k - \theta_m$

On the other hand, the involved inequality constraints reflect the laws governing the power generation-transmission systems and the operating limitations of the equipment, in order to make sure the system security, these restrictions include:

The generation capacity of each generator has some limits. They can be expressed by (5), (6) and (7).

$$Pg_i \min \leq Pg_i \leq Pg_i \max \qquad (5)$$

$$Qg_i \min \leq Qg_i \leq Qg_i \max \qquad (6)$$

$$Vg_i \min \leq Vg_i \leq Vg_i \max \qquad (7)$$

With i=1….. NG, where:

Where NG is the number of power station on the system;

Pg_i *min*, Pg_i *max*: Lower and upper limit of active power of generator i;

Qg_i *min*, Qg_i *max:* Lower and upper limit of reactive power of generator i;

Vg_i *min*, Vg_i *max:* Lower and upper limit of generator voltage i;

Security constraints include the restrictions on magnitude voltages at buses, and transmission line loadings as shown in (8), (9) and (10).

$$V_k \min \leq V_k \leq V_k \max \qquad (8)$$

$$\theta_k \min \leq \theta_k \leq \theta_k \max \qquad (9)$$

$$Fl_{km} \leq Fl_{km} \max \qquad (10)$$

With $k=1...NB$, and $m=1....NB$

Fl_{km} *max:* Maximum power flow through line between nodes k and m;

Transformer tap settings are restricted by the lower and upper limits, as expressed in (11).

$$T_j \min \leq T_j \leq T_j \max \qquad (11)$$

With $j=1...NT$

Where NT is the number of transformers in the system.

If they exist, it is possible modeling environmental restrictions, e.g., maximum limit of total emissions, which can be expressed by (12).

$$\sum_{i=1}^{NG} E_c(Pg_i) \leq ET_c \quad c=1......NC \qquad (12)$$

Where c represent a set of pollutants, e.g., SO_2, CO_2

General analysis of the optimization problems

As it is mentioned in previous paragraphs, in general, a planner confronts optimization problems that are nonlinear and non-convex. Particularly, ED for real system is a large dimension problem, which increases enormously according to the size of analyzed power system. Then, for conventional optimization techniques based on gradient, it proves to be difficult not only to solve them, but at times even; it is very problematical to find feasible solutions. In addition, the traditional solution of optimization problems is based in the supposition that it is known with certainty and precision the variables implicated in the decision model. However, some uncertain parameters, whose definition can come from forecasting models, include some imprecision degree (error), and therefore for the planner or operator the more important issue is not the realization of such forecasting, but the manner how the variability of those parameters can affect the decisions, and how modeling such uncertainty in the decision models.

As expressed in [5], most decisions in the real world are carried out in situations where objectives, constraints, possible actions (solutions space) and their consequences are not known accurately. The fuzzy set theory provides a natural structure to model imprecise relationships or concepts such as: big, polluting, economical, satisfactory, suitable, and so on.

Fuzzy sets and possibility theory

Basic definitions on fuzzy sets are introduced in [6]. Let X be a collection of objects generally denoted by x, then a fuzzy set $\tilde{A}$ in X corresponds to the group of ordered pairs, as expressed in (13).

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) / x \in X\} \quad (13)$$

In reference [7] the possibility theory on the basis of fuzzy sets theory is developed. Zadeh proposed the idea of representing an incomplete state of knowledge by means of a fuzzy set. If for instance, we only know about quantity X that "X is large", it means that the possible values for X are those compatible with the meaning of "large" in the considered context. Such a label is represented by the membership function of a fuzzy set, i.e., $\pi_x = \mu_{large}$, where π_x denotes the possibility distribution describing the more or less possible values for X according to what is known.

A possibility distribution π_x on U is a mapping from U to the unit interval [0,1] attached to the single-valued variable X. The function π_x represents a flexible restriction which constrains the possible values of X according to the available information, with the following conventions:

$\pi_x(u) = 0$ means that X = u is definitely impossible,

$\pi_x(u) = 1$ means that absolutely nothing prevents that X=u

From a possibility distribution, seen as a repository of knowledge about a variable X, one can build different uncertainty measures to characterize what can be said about any event (i.e. a subset of the domain of X). The most commonly used ones are the possibility and necessity measures, denoted by π and N respectively, that are defined in (14) and (15) as follows [8]:

$$\Pi_K(A) = \sup_{u \in A} \min[\mu_A(u), \pi_x(u)] \quad (14)$$

$$N_K(A) = 1 - \Pi_K(A^c) = \inf_{u \notin A} \max[\mu_A(u), 1 - \pi_x(u)] \quad (15)$$

Fuzzy vs. Possibilistic entities

Many applications have been developed in the scope of fuzzy sets theory without taking a lot of attention on the semantics represented by these sets. As a result, a very friendly and solid mathematical structure to combine fuzzy sets has been created, but frequently, this is shown without assigning it to any interpretative structure. When doing it that way the risk of depriving, in guidelines about how and what situations should be used, is suffered by users of this technique. Irretrievably, this situation produces the simple development of senseless operations semantically, leaving to the obtained results without an interpretative structure.

In this point, it is necessary to make a clarification. There is often confusion between fuzzy and possibilistic optimization. Fuzzy and possibilistic entities have different meanings/semantics. Fuzzy and possibility model different entities and the associated solution methods are different.

Fuzzy entities are sets with nonsharp boundaries in which there is a transition between elements that belong and elements that do not belong to the set. In this situation there is no uncertainty [9]. Possibilistic entities are obtained from sets that are classical sets (crisp), but the evidence associated with whether a particular element belongs to the (crisp) set or not, is incomplete or hard to obtain. Then, there is uncertainty [8].

Fuzzy sets can be used to represent constraints in optimization problems, these may relate to two basic semantic: plausibility (uncertainty) and preference (flexibility) [7]. The case of uncertainty is related to uncontrollable or unknown variables, where there is no complete or consistent information about the value that these variables might take within the constraint. In this context, reference to the plausibility that the variable under consideration takes some specific value is done. For this case the restrictions are observed in an unfavourable direction for the objectives, this situation takes place because attention is focused on the occurrence of adverse situations of uncertain variable, and therefore the planner will seek to protect the system from such situations. On the other hand, the flexible case refers to controllable variables, in which it is considered that it is possible to take advantage of the relaxation in the requests of a restriction based in the control on the implicated variable. For this situation, it is emphasized on the preference degrees of the values that it is possible to assign to the variable. Note than converse to the previous semantics, in these circumstances the restrictions are satisfied in the favourable direction to the objectives (relaxation), because the planner's concern is the expansion of the area of feasible solutions by means of a light violation of the requests. At times, this situation even allows getting bigger levels from fulfillment in the attributes of decision (optimization).

In short, when a fuzzy restriction represents the imprecise knowledge about a no-controllable variable, the satisfaction degree of restriction describes necessity degrees (N) caused by the desire of getting a feasible and robust solution in the bigger quantity of possible states of the implicated variable. The previous situation is in total contrast to the case of a fuzzy restriction which contains a controllable decision variable, where the satisfaction degree of restriction describes possibility degrees (π), since it is always possible to select the best suitable value of variable. In this case, it is sufficient that there is a variable value that satisfies the restriction on the best possible way; hence the feasibility in this situation is only expressed in terms of possibility [8].

Results and discussion

Formulation of Fuzzy-Possibilistic Economic Dispatch In the following, a model for ED with fuzzy and possibilistic variables, is presented. For the objective F a triangular membership function has been selected as defined in (16).

$$\begin{aligned} &\mu_F(x) = 1 && if\, F(x) < F_{\min} \\ &\mu_F(x) = 1 - \frac{F(x) - F_{\min}}{F_{\max} - F_{\min}} && if\, F_{\min} \le F(x) \le F_{\max} \\ &\mu_F(x) = 0 && if\, F(x) > F_{\max} \end{aligned} \quad (16)$$

Where, *Fmax* and *Fmin* represent the maximum and minimum admissible values for the objective function, such it is presented in the figure 1.

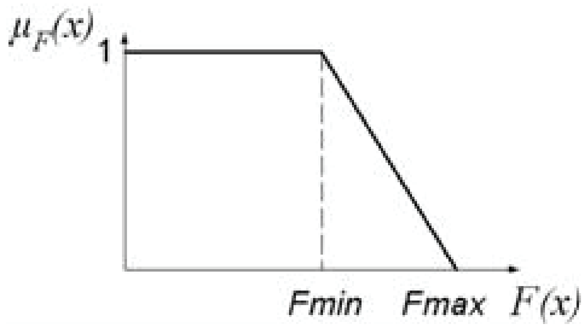

Figure 1 Representation of fuzzy objective

In what follows, it will be presented a flexible form for restrictions associated with controllable variables such as limits of maximum and minimal voltage in the system buses, as well as for the maximum power flow for transmission lines. It is considered that these restrictions are susceptible of some loosening, since in power system real operation, at times the operators recur to relaxation manual of such restrictions in order to achieve the convergence in the power flow. Of course, such relaxation and its representation by means of membership functions of fuzzy sets, it will be based fundamentally in the knowledge of the operator on the system behavior. The equations for maximum and minimum case are and , respectively; and the graphic representation is shown in the figure 2.

$$\begin{aligned} &\mu_{G1}(x) = 1 && if\, G1(x) \le G1_{\max} \\ &\mu_{G1}(x) = \frac{(G1_{\max} + dG1_{\max}) - G1(x)}{dG1_{\max}} && if\, G1_{\max} \le G1(x) \le G1_{\max} + dG1_{\max} \\ &\mu_{G1}(x) = 0 && if\, G1(x) \ge G1_{\max} + dG1_{\max} \end{aligned} \quad (17)$$

Where $G1$ can represent for example: V_k, Fl_{km}, θ_k, Ec among others; and $dG1_{max}$ denote the maximum admissible variation of function G1.

$$\mu_{G2}(x)=1 \quad if \quad G2(x)\geq G2_{\min}$$

$$\mu_{G2}(x)=\frac{G2(x)-(G2_{\min}-dG2_{\min})}{dG2_{\min}} \quad if \quad G2_{\min}\geq G2(x)\geq G2_{\min}-dG2_{\min} \tag{18}$$

$$\mu_{G2}(x)=0 \quad if \quad G2(x)\leq G2_{\min}-dG2_{\min}$$

Where $G2$ can represent V_k, θ_k, among others; and $dG2_{min}$ denote the minimum admissible variation of function G2.

$dG1_{max}$ and $dG2_{min}$ can be obtained by experts of power system operation.

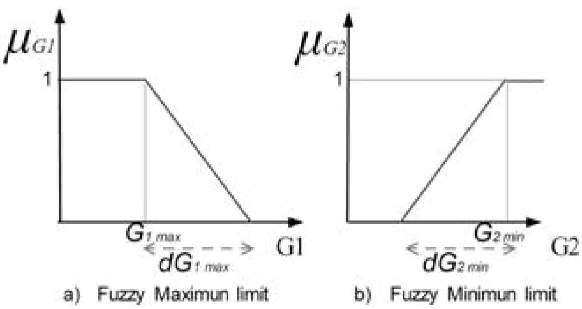

Figure 2 Representation of fuzzy constraints

Next, it is presented possibilistic restrictions related to uncertain variables (no-controllable), e.g., the power flow equations in each bus. Since equation depends on a previously established demand (forecasted) which could come true or not. Then, the operator will seek to foresee, how the ignorance of precise values can affect his decisions. Basically, given the available information, the presented formulation is attempted to observe in what extent, the planner will allow to a cost increment and emission decrement, while satisfying the requests of security system in front of the occurrence of adverse events, in this specific case, the event of a larger demand than the forecast. In this sense, the uncertainty on an event becomes a decision criterion, where the best decision will be that one which satisfies the decision criteria and the flexible restrictions, for the larger quantity of possible events, and that is evaluated by a necessity measure (N), as expressed in 19.

$$\mathrm{N}_H(u)=1-\pi_H(u) \tag{19}$$

Where, the H represents the uncertain variables Pdk and Qdk, which are expressed through a possibility distribution, as it is indicated in the figure 3. On this figure, it is possible to observe a value of the variable H which has the maximum possibility of happening, and two extreme data which are determined by adding and subtracting an estimated deviation with respect to the value of maximum possibility.

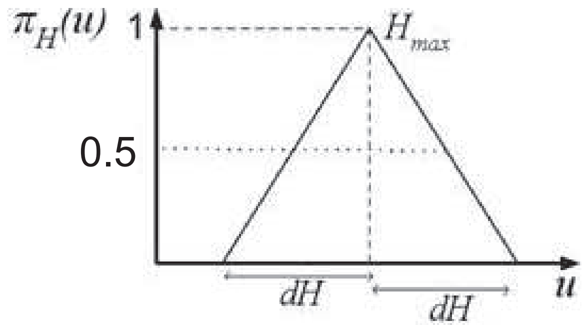

Figure 3 Representation of possibilistic demand

For the ED, the objective function presented in the context of fuzzy and possibilistic restrictions are defined by 20, 21 and 22.

$$\max\Phi=\max_{x\in X}\left\{\min_{u\in E}\left\{\max\left(1-\pi_E(u)\ ,\ \mu_{\tilde{D}}(x(u))\right)\right\}\right\} \tag{20}$$

Where:

$$\pi_E(u)=\min\left\{\pi_{Pk}(u),\pi_{Qk}(u)\right\} \tag{21}$$

$$\mu_{\tilde{D}}(x(u))=\min\begin{Bmatrix}\mu_F(x(u)),\mu_{E_c}(x(u)),\\ \mu_{V_{k\max}}(x(u)),\mu_{V_{k\min}}(x(u)),\\ \mu_{\theta_{k\max}}(x(u)),\mu_{\theta_{k\min}}(x(u)),\\ \mu_{Fl_{km\max}}(x(u))\end{Bmatrix} \tag{22}$$

Here, "x" represents decision variables, i.e., power generation (P_{Gi} and Q_{Gi}), "u" represents the value that an uncertain variable can take, "π" is a possibility distribution that is assigned to each uncertain variable, and "μ" is the satisfaction level of the decision attributes and restrictions (membership function).

The proposed model is a nonlinear integer mixed problem, which can be transformed into an iterative linear integer mixed problem by means of approach describes in Sakawa [10].

Simulations

In order to evaluate the proposed model, the IEEE 30 bus system is used. First, it tested the system with flexible restrictions on the maximum and minimum voltages, which shows that the suggested model is reduced to Bellman model on the absence of uncertainties 5. For this test, the inferior crisp limit of magnitude voltage for all buses is 0.95 p.u. The superior crisp limit of magnitude voltage is 1.05 p.u. for slack bus and all load buses, while the upper crisp limit of all other generator buses is 1.1 p.u. It is desired to get a reduction cost of 0.5% (*dF*). In order to achieve this task, the planner could decide that it is possible a maximum admissible relaxation of voltage in both limits (up, down) is 0.05 pu, except for buses whose upper crisp limit is 1.1 pu where no relaxation is allowed. When the model is executed, it is obtained as a result a solution with a satisfaction level of 0.43, indicating that it is possible to get a satisfactory answer from the economic viewpoint by relaxing (increasing, and decreasing) the voltage limits up to 53%, e.g. 1.05 to 1.0785 pu and 0.95 to 0.9215 pu as new limits, as illustrated in tables 1, 2 and figure 4.a. These results show a reduction of 0.22%, which in systems of considerable size, can represent significant savings in monetary terms. It is important to highlight that any environmental objective had been considered at this time. Then, total emission levels for ED deterministic and ED fuzzy are only state variables.

Next, the system is tested both with flexible restrictions on the maximum and minimum voltages, and with restrictions related to uncertain active and reactive demands, and emission levels of power stations. For demand, it is considered that the maximum value of uncertainty is 2% and 1% compared with the active and reactive predicted values of demand, respectively; and 5% of deviation respect to expected emission level for each generator. Additionally, the planner could allow an increase in the cost of about 5% with respect to ED deterministic, in order to avoid adverse situations related to uncertain demand or pollutants.

Table 1 Optimal values for power generation

Generator	***ED deterministic***	***ED fuzzy***	***ED fuzzy possibilistic***
PG i	MW	MW	MW
1	176.15	176.73	178.33
2	48.81	48.74	49.21
3	21.50	21.38	21.58
4	22.02	21.40	22.63
5	12.18	11.98	12.39
6	12	12	12

Table 2 Results of optimization process

		ED deterministic	***ED fuzzy***	***ED fuzzy possibilistic***
Economic cost	*\$/h*	801.66	799.90	813.52
System loss	*MW*	9.27	8.83	9.17
CO_2	*T/h*	23.10	24.26	21.87
SO_2	*T/h*	0.28	0.26	0.23
Buses with V>=Vmax=1.05		5.00	25.00	23.00
		Satisfaction Level φ	0.43	0.63

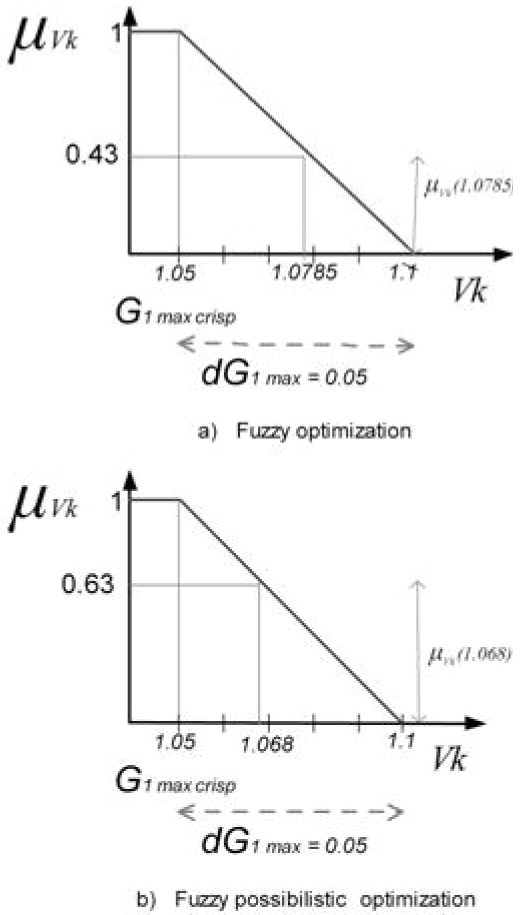

Figure 4 Interpreting μ in fuzzy and possibilistic ED

It is obtained as a result a solution with a level of certainty and satisfaction Φ of 0.63, indicating that it is possible to achieve a satisfactory response from the economic view point, by means of relaxing the voltage limits up to 37% from maximum admissible deviation for $V_k max$ ($dG1_{max} = dV_k max = 0,05\ pu$), e.g. relaxing from 1.05 to 1.0685 pu (see figure 4.b), and from 0.95 to 0.931 pu, as new limits, while meeting an unexpected increase of demand up to 1.26% (value associated with the satisfaction level) as shown in tables 1, 2 and figure 5. Here, there is no cost savings, but the crucial aspect to consider is that the operator has a certainty level of 0.63 (N=0.63) to meet an unexpected increase in demand while the power system security gets satisfied, of course, relaxing to some extent the voltage limits (μ=0.63). This is shown in the figure 5. Additionally, it is considered the uncertainty about the emission levels of generators; the proposed mechanism suggests that the obtained solution provides a certainty level of 0.63 for the likelihood of achieving environmental objectives.

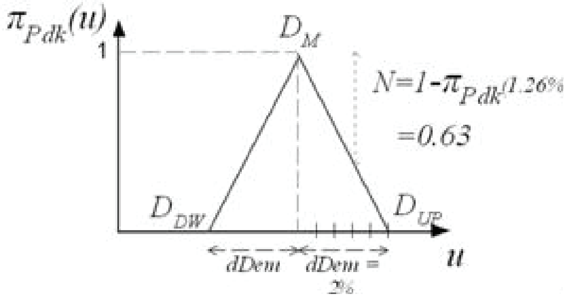

Figure 5 Interpreting π in fuzzy-possibilsitic DE

Conclusions

This paper presents a complementary approach to the use of fuzzy sets in the optimization process involving power systems, specifically the ED. This application considers not only the traditional flexible approach of fuzzy sets, shown in other applications, but also distinguishes the inclusion of uncertainty into the decision-making process through possibility distributions clearly, and providing a structure for the interpretation of the problem solution. This tool can be extended to multicriteria approaches, here; environmental criterion was included in the optimization process. This procedure has the advantage that uncertainty is not just a parameter, but a criterion inside decision process (optimization).

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