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An IGDT Based Robust Decision Making Tool for DNOs in Load Procurement under Severe Uncertainty

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Abstract—**This paper presents the application of Information Gap Decision Theory (IGDT) to help the Distribution Network Operators (DNOs) in choosing the supplying resources for meeting the demand of their customers. The three main energy resources are pool market, Distributed Generations (DGs) and the bilateral contracts. In deregulated environment, the DNO is faced with many uncertainties associated to the mentioned resources which may not have enough information about their nature and behaviors. In such cases, the classical methods like probabilistic methods or fuzzy methods are not applicable for uncertainty modeling because they need some information about the uncertainty behaviors like Probability Distribution Function (PDF) or their membership functions. In this paper, a decision making framework is proposed based on IGDT model to solve this problem. The uncertain parameters considered here, are as follows: price of electricity in pool market, demand of each bus and the decisions of DG investors. The robust strategy of DNO is determined to hedge him against the risk of increasing the total cost beyond what he is willing to pay. The effectiveness of the proposed tool is assessed and demonstrated by applying it on a test distribution network.**

Index Terms—**Distributed Generation; Information Gap Decision Theory ; Bilateral contracts ; Uncertainty ; Risk.**

I. INTRODUCTION

The presence of Distributed Generations (DGs) in distribution networks, has been become a familiar issue for Distribution Network Operators (DNO). These generating units can play important role in increasing the reliability of supply [1], emission reduction [2], [3], reducing the needs for upgrading the transmission [4] or distribution networks [5] and active loss reduction of distribution networks [6]. The regulatory frameworks which determine the authorities of DNO in dealing with DG units differ from country to country. In some countries the DNO can invest in DG units and therefore he can decide about the location, size and DG technology based on his interests and requirements. However, in some other countries, the DNOs are not allowed to own DG units [7] and just have to maintain the security and efficiency of distribution network to meet the demand growth and serving the customers [8], [9]. In such frameworks, the DNO tries to hedge its consumers against the high prices of the pool market. In order to do so, he has three energy resources for energy procurement namely, pool market, DG units installed (or to be installed) in its territory and bilateral contracts. The problem is that

the DNO can not be certain about the values of demands in each bus, price of energy in pool market and decisions of DG investors. There are several methods proposed in the literature for dealing with uncertainties of the mentioned parameters. These methods can be categorized into three main principal categories: probabilistic methods like Monte Carlo simulation [10], Point Estimate Method [11], [12], Latin Hyper cube sampling [13]; possibilistic methods [14]; hybrid probabilistic-possibilistic [15]. All of the three mentioned models need some historic data of specific characteristic of the behavior of the uncertainties. For example, the probabilistic methods need PDF of uncertain values and the same applies for possibilistic methods which need membership functions of uncertain variables. They can not be much helpful when the DNO is subject to severe uncertainty and no PDF or membership function can be specified for uncertain parameters. A novel framework was proposed named Information Gap Decision Theory (IGDT) in [16] which is powerful in cases of severe uncertainty [17]. The IGDT model neither needs the PDF nor membership function of uncertain variables. Instead of these data it focuses on what is known and what is needed to be known [18]. The application of this method in power system has already been investigated in energy procurement strategy for large consumers [19] and also bidding strategy in purchasing from different energy resources [20], [21]. In this paper, a novel energy procurement strategy is proposed which helps the DNO to choose its energy resources when he is faced with differently uncertainties. The main contribution of this paper is as follows:

- A robust energy procurement strategy is proposed for DNO when the price of electricity in pool market, electric demands and decisions of DG investors are uncertain and no PDF or membership function of them is available.

This paper is set out as follows: section II gives a brief introduction to IGDT model, section III presents the problem formulation, the simulation results of the proposed model are presented in section IV and finally, section V states the findings of this work.

II. INFORMATION GAP DECISION THEORY

The Information Gap Decision Theory (IGDT) is a non-probabilistic and non-fuzzy method for quantification of uncertainty. In this context, the uncertainty is defined as the distance between what is known (or predicted) and what may happen in reality [16]. One of the applications of this tool

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is helping the decision makers to maximize the robustness of their decisions against the failures. The robustness is defined as the immunity of the minimum requirement satisfaction at presence of uncertain parameters [16].

A. Uncertainty Modeling

There are several models in IGDT method for presenting the uncertainty of parameters. Here, the envelope bound model [16] is used, as follows:

$$x \in U(\alpha, \tilde{x}) \tag{1}$$
$$U(\alpha, \tilde{x}) = \left| \frac{x - \tilde{x}}{\tilde{x}} \right| \leq \alpha$$

Where, α is the uncertainty horizon of parameter x, $\tilde{x}$ is the predicted (most expected) value of x and $U(\alpha, \tilde{x})$ is the set of all values of x whose deviation from $\tilde{x}$ is nowhere greater than $\alpha\tilde{x}$. It should be mentioned that both of the x and α are uncertain.

B. System Requirements

The system requirement is highly dependent on the nature of the problem under study. This can be the minimum revenue a company may expect to gain or the maximum money a customer may be willing to pay. Two important subjects should be clarified; first, reaching to the minimum requirements is subject to risk because of uncertain parameters of the problem. Second, the goal is not minimizing the cost that customer should pay or maximizing the revenue that a company may gain. The main purpose of IGDT is to help the decision maker to set the decision variables to the values which hedges him against the risk of not reaching the minimum requirements at presence of the uncertainties of uncontrollable parameters. In this paper, the minimum requirement is defined as not surpassing a predefined limit, i.e. r_c, for a given cost function, i.e. $f(x, \bar{q})$, as follows:

$$\text{Goal :} f(x, \bar{q}) \leq r_c \tag{2}$$
$$\text{Subject to}$$
$$H(x, \bar{q}) = 0, G(x, \bar{q}) \geq 0$$

Where, x is the input parameter and $\bar{q}$ is the decision variable. H and G are the equality and inequality constraints, respectively.

C. Robustness

The robustness of a decision $\bar{q}$ based on the requirement r_c, i.e. $\hat{\alpha}(\bar{q}, r_c)$, is defined as the maximum value of α at which the decision maker is sure that the minimum requirements are always satisfied [16], as follows:

$$\hat{\alpha}(\bar{q}, r_c) = \max \alpha \tag{3}$$
$$St :$$
$$\text{minimum requirements are always satisfied}$$

The decision making policy is defined as finding the decision variables, i.e. $\bar{q}$, which maximizes the robustness, as formulated below:

$$\max_{\bar{q}} \hat{\alpha}(\bar{q}, r_c) \tag{4}$$
$$\forall x \in U(\alpha, \tilde{x}) \tag{5}$$
$$\implies f(x, \bar{q}) \leq r_c$$
$$H(x, \bar{q}) = 0, G(x, \bar{q}) \geq 0$$

III. PROBLEM FORMULATION

The described decision making tool is formulated and presented in this section. The decision variables are defined as the quantities of energy purchased from the pool market, DG units and the bilateral contracts. The assumptions used in problem formulation, constraints and the objective function are explained next.

A. Assumptions

The following assumptions are employed in problem formulation:
- The DG unit are considered to be negative loads.
- The daily load variation is modeled using a load duration curve which is divided into N_{dl} discrete demand levels. Assuming a base value of demand in bus i, i.e. $S_{i,base}^D$, a Demand Level Factor of DLF_{dl} and a demand growth rate of ϵ_D, the predicted value of demand in bus i, in year t and in demand level dl, is described as:

$$\tilde{S}_{i,t,dl}^D = S_{i,base}^D \times DLF_{dl} \times (1 + \epsilon_D)^t \tag{6}$$

- The electricity price, i.e. $\lambda_{t,dl}$, is a function of behaviors of market players. The variation of predicted electricity price in each demand level is modeled by multiplication of price growth until year t, i.e. $(1 + \epsilon_\lambda)^t$ and base price, i.e. λ_{base}, and a Price level Factor in demand level dl, i.e. PLF_{dl}. The predicted value of electricity price in pool market, i.e. $\tilde{\lambda}_{t,dl}$, is calculated as follows:

$$\tilde{\lambda}_{t,dl} = \lambda_{base} \times PLF_{dl} \times (1 + \epsilon_\lambda)^t \tag{7}$$

Where, ϵ_λ is the price growth rate.

B. Uncertainty modeling of input parameters

The uncertainties of electricity price in year t and demand level dl, i.e. $\lambda_{t,dl}$, demand of bus i in year t and demand level dl, i.e. $S_{i,t,dl}^D$ and decisions of DG investors about the capacity of DG units, i.e. C_i^{dg}, are modeled using (1) as follows:

$$\lambda_{t,dl} \in U(\zeta, \tilde{\lambda}_{t,dl}) \tag{8}$$
$$C_i^{dg} \in U(\gamma, \tilde{C}_i^{dg}) \tag{9}$$
$$S_{i,t,dl}^D \in U(\alpha, \tilde{S}_{i,t,dl}^D) \tag{10}$$

C. Constraints

a) Power Flow Constraints: The power flow equations that should be satisfied in year t and demand level dl are:

$$P_{i,t,dl}^{net} = -P_{i,t,dl}^{D} + P_{i,t,dl}^{dg} \tag{11}$$

$$Q_{i,t,dl}^{net} = -Q_{i,t,dl}^{D} + Q_{i,t,dl}^{dg}$$

$$P_{i,t,dl}^{net} = V_{i,t,dl} \sum_{j=1}^{N_b} Y_{ij} V_{j,t,dl} cos(\delta_{i,t,dl} - \delta_{j,t,dl} - \theta_{ij})$$

$$Q_{i,t,dl}^{net} = V_{i,t,dl} \sum_{j=1}^{N_b} Y_{ij} V_{j,t,dl} sin(\delta_{i,t,dl} - \delta_{j,t,dl} - \theta_{ij})$$

Where, $P_{i,t,dl}^{D}$ and $Q_{i,t,dl}^{D}$ are the active and reactive power produced by DG unit in year t and demand level dl, respectively.

b) Operating limits of DG units: The DG units should be operated considering the limits of their primary resources, i.e.:

$$P_{i,t,dl}^{dg} \leq \overline{P}_{lim}^{dg} \tag{12}$$

The power factor of DG unit is kept constant [5] in all demand levels.

c) Voltage profile: The voltage magnitude of each bus should be kept between the safe operating limits. These limits are dependent on operating condition of the system under study.

$$V_{min} \leq V_{i,t,dl} \leq V_{max} \tag{13}$$

d) Thermal limit of feeders and substation:: To maintain the security of the feeders and the substation, the flow of current/energy passing through them should be kept below the feeders/substation capacity limit, as follows:

$$I_{t,dl}^{\ell} \leq I_{max}^{\ell} \tag{14}$$

$$S_{t,dl}^{grid} \leq S_{max}^{grid} \tag{15}$$

1) Total Costs: The total cost that the DNO should pay, has three components including the cost of electricity purchased from pool market, the costs of purchasing energy from DG units and finally the costs of bilateral contracts. Each term is explained next: The total cost of energy purchased from pool market is calculated as follows:

$$PC = \sum_{t=1}^{T} \sum_{dl=1}^{N_{dl}} \lambda_{t,dl} \times P_{t,dl}^{grid} \times \tau_{dl} \times \frac{1}{(1+d)^t} \tag{16}$$

Where, d is the discount rate and $P_{t,dl}^{grid}$ is the active power purchased from pool market.
The total costs of the purchasing electricity from DG units can be calculated as:

$$DGC = \sum_{t=1}^{T} \sum_{i=1}^{N_b} \sum_{dl=1}^{N_{dl}} \lambda_{dg} \times P_{i,t,dl}^{dg} \times \tau_{dl} \times \frac{1}{(1+d)^t} \tag{17}$$

The total cost of the bilateral contracts is calculated as follows:

$$BcC = \sum_{t=1}^{T} \sum_{dl=1}^{N_{dl}} \rho \times P_{t,dl}^{bc} \times \tau_{dl} \times \frac{1}{(1+d)^t} \tag{18}$$

Where, $P_{t,dl}^{bc}$ is the active power purchased through bilateral contract.
The total cost is the sum of all mentioned terms, as follows:

$$TC(\lambda_{t,dl}, C_i^{dg}, S_{i,t,dl}^{D}) = PC + DGC + BcC \tag{19}$$

D. Minimum Requirement

The DNO is not trying to minimize the total cost. Instead of that, he will try to minimize the risk of experiencing high prices by its customers. For this reason, he will try to keep the total cost below an acceptable level, i.e. r_c. This value can be defined in various ways but it is reasonable to define it as a percent of the predicted total cost, i.e. $\tilde{TC}$, as follows:

$$\tilde{TC} = \min_{\bar{q}} TC(\tilde{\lambda}_{t,dl}, \tilde{C}_i^{dg}, \tilde{S}_{i,t,dl}^{D}) \tag{20}$$

$$\bar{q} = [S_{i,t,dl}^{dg}, S_{t,dl}^{grid}, P_{t,dl}^{bc}]$$

The minimum requirement is defined as follows :

$$TC(\lambda_{t,dl}, C_i^{dg}, S_{i,t,dl}^{D}) \leq r_c \tag{21}$$

$$r_c = (1+\sigma) \times \tilde{TC}$$

Where, σ is the percent of tolerable increase of total cost.

E. Objective Function

There are three uncertain parameters in this problem formulation. Robustness is defined as the minimum uncertainty horizon in which all requirements are satisfied. To find the optimum decision, the DNO should maximize the robustness against the uncertainties of all three parameters, as follows: the maximum risk occurs when the prices and demands are at their highest level, i.e. $\lambda_{t,dl} = (1+\zeta) \times \tilde{\lambda}_{t,dl}$, $S_{i,t,dl}^{D} = (1+\alpha) \times \tilde{S}_{i,t,dl}^{D}$ and also the lowest investment is done by DG investors in the distribution network, i.e. $C_i^{dg} = (1-\gamma) \times \tilde{C}_i^{dg}$. In other word, the worst conditions which may cause the maximum risk are considered for uncertain parameters and then it is tried to set the decision variables, i.e. $\bar{q}$ to be sure that the minimum requirements are always satisfied, as follows:

$$\max_{\bar{q}} OF \tag{22}$$

$$OF = \min(\alpha, \zeta, \gamma)$$

$$\lambda_{t,dl} = (1+\zeta) \times \tilde{\lambda}_{t,dl}$$

$$C_i^{dg} = (1-\gamma) \times \tilde{C}_i^{dg}$$

$$S_{i,t,dl}^{D} = (1+\alpha) \times \tilde{S}_{i,t,dl}^{D}$$

$$St: (6) \text{ to } (21)$$

Since the minimum value of α, ζ, γ is maximized then solving the (22), gives the robustness values of load procurement strategy versus against different uncertainties.

IV. CASE STUDY

In this section, the proposed methodology is applied to a 9-bus test distribution network which is shown in Fig.1 for demonstrating its ability. The planning horizon, i.e. T, is considered to be 5 years.
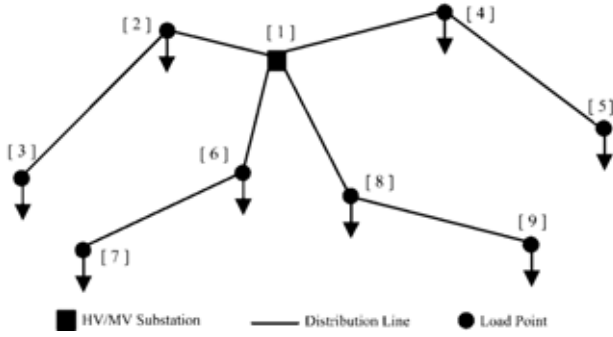
Fig. 1.   Single-line diagram of the test system

The objective of this case study is to find a robust strategy for load supply by DNO at presence of different uncertainties.

A. Data

The technical data of the test distribution network is given in [3], [14], [22].
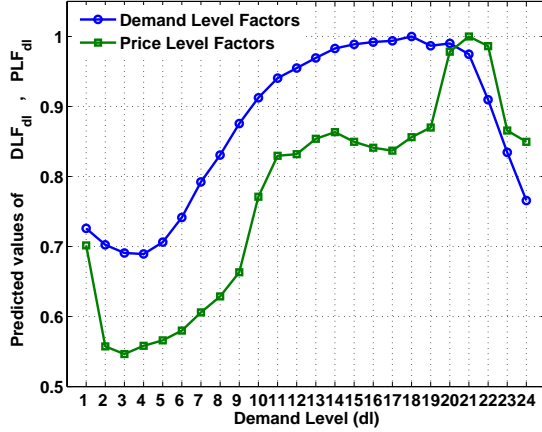

Fig. 2.   Variation of demand and price level factors in each demand level

This network consists of a 132/33kV substation with $S^{grid}_{max} = 40MVA$ capacity and 4 feeders with $I^{\ell}_{max} = 210A$ and 8 aggregated loads which their base values are given in [3]. In this paper, the DG technology is assumed to be Gas turbine [23] but this is not limiting the ability of the proposed model for considering other DG technologies like renewable energy resources. The probabilistic methods are used to model the uncertainties of renewable DG technologies, however, some parameters of their Probability Distribution Function (PDF) are neither the structure of the uncertainty of such data is neither probabilistic density nor possibilistic , this is where IGDT method can be usefull as it is proposed in [24]. For each year, $N_{dl} = 24$ demand level factors, i.e. DLF_{dl}, and also 24 price level factors, i.e. PLF_{dl}, are considered; The duration of each demand level, i.e. τ_{dl}, is assumed to be 365 hours. The values of actual demand and average price of a realistic pool market of California ISO [25], from January 2008 to January 2009, are used to produce the predicted values of DLF_{dl} and PLF_{dl}. The variation of demand and price level factors are depicted in Fig.2. The price of active power purchased

through bilateral contract is assumed to be fixed and equal to $85\$/MWh$ for all demand level factors. The price of energy purchased from DG units can be different for each demand level but here, for simplicity and without loss of generality, it is assumed to be fix and equal to $\lambda_{dg} = 90\$/MWh$. The base price of pool market, i.e. λ_{base}, is $98\$/MWh$. For technical reasons it is assumed that there is a maximum limit for the energy purchasable through bilateral contracts equal to 15 MW. The predicted values of the capacity of investor-owned DG units are given in Table.I Other simulation assumptions are presented in Table.II.

TABLE I
PREDICTED VALUES OF DG CAPACITIES

Bus (i)	$\tilde{C}^{dg}_i (MVA)$
3	3.5
6	1
9	2.5

TABLE II
DATA USED IN THE STUDY

Parameter	Unit	Value
$\epsilon_D = \epsilon_\lambda$	%	2
d	%	12.5
V_{max}	Pu	1.05
V_{min}	Pu	0.95

The formulated problem was implemented in GAMS environment [26].

B. Results

First of all, the minimum value of total cost for load procurement is found using (20). The value of predicted minimum total cost, i.e. $\tilde{TC}$, is $58503753.09\$$. Now, (22) is solved for different values of σ. The parameter σ is varied from 0 to 100% and for each r_c the optimum values of decision variables, i.e. $S^{dg}_{i,t,dl}$, $S^{grid}_{t,dl}$ and $P^{bc}_{t,dl}$, are found. The variations of robustness against the uncertainty of electricity price, load variation and DG-investor's decisions versus the variations of σ are depicted in Fig.3. As already defined, the value of α shows the uncertainty of the demand values in each bus in Fig.3. The value of $\hat{\alpha}$ begins from 0 in $\sigma = 0$ and reaches to its maximum value, $\hat{\alpha} = 0.0832$ in $\sigma = 14\%$. This means that although the requirement constraint is getting more relaxed (after $\sigma = \%14$) but the constraints of the problem do not let the DNO to make his strategy more robust against the uncertainties of demand. The solution for this case can be investment in network components or reconfiguration of the distribution network. The parameter ζ shows the uncertainty of electricity price. The variation of robustness, i.e. $\hat{\zeta}$, against this parameter begins from 0 to $\hat{\zeta} = 0.82962$ as shown in Fig.3. The interesting point of this parameter is that it remains zero until $\sigma = 38\%$. This means the DNO should expect the risk of at least 38% of increase in the total cost he should pay due to the electricity price uncertainty. Increasing the amount of bilateral might be helpful in this case. The final uncertainty horizon is γ which is related to decisions of DG investors. As it is observable in Fig.3, the robustness against this parameter,
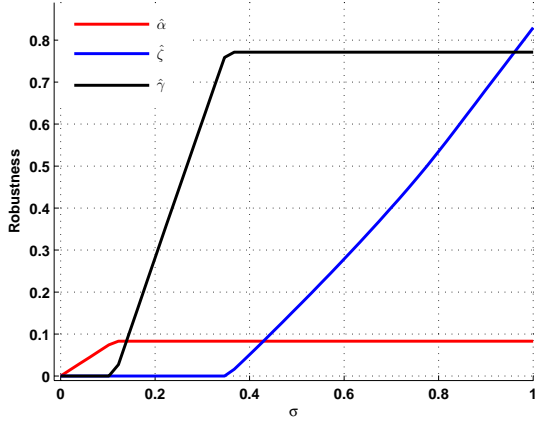
Fig. 3. Variation of Robustness against different uncertainties versus the variation of σ

i.e. $\hat{\gamma}$ is zero until $\sigma = 12\%$ and after this limit it will increase until it reaches to its maximum value $\hat{\gamma} = 0.77129$. This means that the DNO should expect the risk of 11.5% increase in the total cost he should pay due to the uncertain decisions of DG investors. The value of $\hat{\gamma}$ gives the DNO an insight about the maximum acceptable deviation of decisions of DG-investors with the predicted values of their performance.
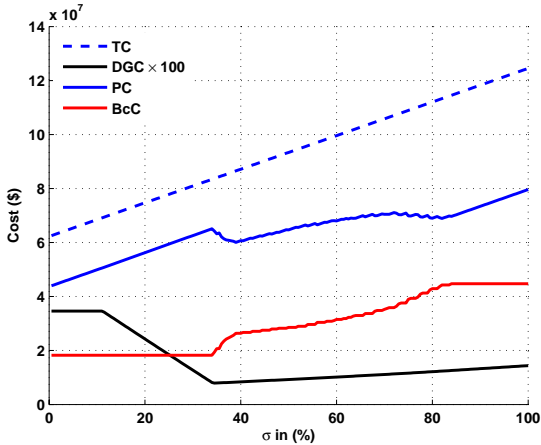

Fig. 4. Variation of Different cost values versus the variation of σ

In other words, the DNO should convince them to invest at least $(1-\hat{\gamma})\%$ of their predicted values to be immune upto $\sigma\%$ of increase of predicted minimum total cost, i.e. $\tilde{TC}$, he should pay. As it is expected, with increasing r_c and the degree of relaxation of cost constraint, the values of robustness against different uncertainties show a non-decreasing behavior. It is reasonable because when the DNO accepts to pay more it will be less in risk of paying more than what he expects.

The variations of Total cost, i.e. TC, Pool market cost, i.e. PC, Bilateral contract Costs, i.e. BcC, and finally DG unit Costs, i.e. DGC, are depicted in Fig.4 versus the variations of σ.

The total cost, i.e. TC, shows a monotonic increase with σ. The cost associated to purchasing power from DG units,

i.e. DGC, is constant from σ =until $\sigma = 14\%$ and then starts decreasing until $\sigma = 38\%$ where reaches to $91009\$$. For the values of σ bigger than 35%, the value of DGC remains constant. The value of BcC shows a non-decreasing behavior until $\sigma = 84\%$ which will be constant and equal to $44739000\$$.
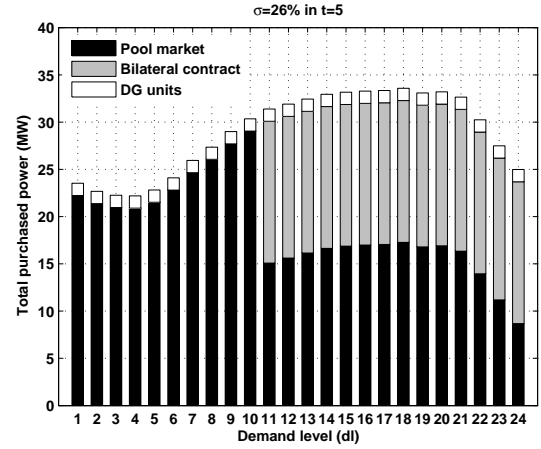

Fig. 5. Load procurement strategy from different resources in year $t = 5$ and $\sigma = 26\%$

The load procurement strategy is shown in Fig.5 for year $t = 5$ and $\sigma = 26\%$. The algorithm proposes DNO to use the bilateral contract just in $dl = 10$ to 24 and in other demand levels buy its energy from pool market and DG units. In the proposed strategy, the total cost, DG cost, pool market cost and bilateral cost are 72544653, 227528, 54090540, 18226584 $, respectively. It should be noted that these values are valid just if the values of uncertainty horizons remain below their maximum values as indicated in Fig.3.

V. CONCLUSIONS

This paper presents the application of a novel decision making tool, i.e. IGDT, for distribution network operator when he is faced with different severe uncertainties. The uncertain parameters considered in this paper are electricity price, demands and decisions of DG investors. The decision variables are the amounts of energy purchased from pool market, DG units and bilateral contracts. The IGDT model is applied to a test system and its flexibility and effectiveness is demonstrated.

LIST OF SYMBOLS AND ABBREVIATIONS

Indices

i, j	Bus
dl	Demand level
ℓ	Feeder
t	Year

Constants

λ_{base}	Base price of each MWh electricity in pool market
DLF_{dl}	Demand level factor in demand level dl
d	Discount rate
τ_{dl}	Duration of demand level dl
PLF_{dl}	Price level factor in demand level dl

ρ	Price of each MWh in bilateral contracts
$\epsilon_D, \epsilon_\lambda$	Rate of demand and electricity price growth
I^ℓ_{max}	Thermal limit of feeder ℓ
S^{grid}_{max}	Thermal limit of substation

Variables

$P^D_{i,t,dl}$	Active power demand in bus i, in year t in demand level dl
$P^{grid}_{t,dl}$	Active power purchased from grid in year t and demand level dl
$P^{dg}_{i,t,dl}$	Active power injected by a dg in bus i, in year t and demand level dl
$S^{grid}_{t,dl}$	Apparent power imported from grid in year t and demand level dl
$S^{dg}_{i,t,dl}$	Apparent power of dg installed in bus i, in year t and demand level dl
$P^D_{i,base}$	Base active power demand in bus i in first year
$Q^D_{i,base}$	Base reactive power demand in bus i in first year
$S^D_{i,base}$	Base apparent power demand in bus i in first year
λ_{base}	Base price of power purchased from the grid
C^{dg}_i	Capacity of DG in bus i
$I^\ell_{t,dl}$	Current magnitude of ℓth feeder in year t and demand level dl
$P^{net}_{i,t,dl}$	Net active power injected to bus i, in year t and demand level dl
$Q^{net}_{i,t,dl}$	Net reactive power injected to bus i, in year t and demand level dl
N_b	Number of buses in the network
N_{dl}	Number of considered demand levels
λ_{dg}	Price of each MW power purchased form dg units.
$\hat{\zeta}(\sigma)$	Robustness function against uncertainty of electricity price
$\hat{\gamma}(\sigma)$	Robustness function against uncertainty of DG capacities
$\hat{\alpha}(\sigma)$	Robustness function against uncertainty of electric demand
$Q^{dg}_{i,t,dl}$	Reactive power injected by a dg in bus i, in year t and demand level dl
$Q^D_{i,t,dl}$	Reactive power demand in bus i, in year t in demand level dl
PC	Total cost paid to pool market for purchasing electricity
DGC	Total cost paid to pool market for purchasing electricity
BcC	Total cost paid for bilateral contracts
TC	Total cost that DNO should pay
$\overline{P}^{dg}_{lim}$	Upper safe operating limit of DG unit
ζ	Uncertainty horizon of electricity price
γ	Uncertainty horizon of DG capacities
α	Uncertainty horizon of electricity demand

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