# Power Market Long-Term Stability: A Hybrid MADM/GA Comprehensive Framework

Mohsen Parsa Moghaddam, Mohammad Kazem Sheik-El-Eslami, and Shahram Jadid

***Abstract*—Stabilizing the long-term electricity markets by providing new generation resources is one of the most important challenges that are surfaced to the industry regulators. To deal with this complex problem, this paper proposes a comprehensive multiple attribute decision making (MADM) framework, in which the genetic algorithm (GA) is used to model the investment decisions of the market generation firms. The fitness function of the GA is itself a decentralized optimization problem that simulates the short-term behavior of these profit-oriented firms. A simple fuzzy inference system and an elasticity relation between price and demand represent the power market, as the link among all firms. The framework is augmented by tradeoff/risk analysis to incorporate the effects of the uncertainties. Finally, a realistic case study is presented to show the advantages of the proposed framework.**

***Index Terms*—Competitive electricity markets, decision support systems, fuzzy inference systems (FIS), game theory, generation expansion planning (GEP), genetic algorithm (GA), market long-term stability, neural networks, risk analysis.**

## I. NOMENCLATURE

### A. Indices

| | |
|---|---|
| $e$ | Generation firms. |
| $h$ | Hydro units. |
| $\ell$ | Load levels. |
| $m$ | Expansion candidates. |
| $s$ | Seasons. |
| $t$ | Thermal units. |
| $y$ | Years. |

### B. Parameters

| | |
|---|---|
| $a_{y,s,\ell}$ | Slope of demand elasticity function in load level $\ell$, season $s$, year $y$ ($\ell sy$) [MW/($/MWh)]. |
| $A_{y,s,h}$ | Hydro inflows for hydro unit $h$ in $sy$ [MWh]. |
| $b_{y,s,\ell}$ | Total demand at zero price in $\ell sy$ [MW]. |
| $d_{y,s,\ell}$ | Duration of $\ell sy$ [h]. |
| $D_{y,s,\ell}$ | Total demand of $\ell sy$ [MW]. |
| $E$ | Number of price-maker firms. |
| $H_t$ | Quadratic heat rate function of thermal unit $t$ [MBtu/h]. |
| $L,S,Y$ | Number of load levels, seasons, and years in planning horizon. |
| $M_e$ | Number of new candidate technologies. |
| $N_{e,h}$ | Number of hydro units belonging to firm $e$. |
| $N_{e,t}$ | Number of thermal units belonging to firm $e$. |
| $\overline{p}_h$, $\underline{p}_h$ | Maximum and minimum generation capacity of hydro unit $h$ [MW]. |
| $\overline{p}_t$, $\underline{p}_t$ | Maximum and minimum generation capacity of thermal unit $t$ [MW]. |
| $PL$ | Total peak load of the system [MW]. |
| $\underline{q}_{y,s,\ell}$ | Total power sold in the contractual market $\ell sy$ [MW]. |
| $\overline{R}_h$, $\underline{R}_h$ | Maximum and minimum hydro energy reserve of hydro unit $h$ [MWh]. |
| $s_e$ | Market share of firm e [%] |
| $t_y$ | Discount rate [pu]. |
| $TG$ | Total Generation capacity of the system [MW]. |
| $TR_y$ | Annual transmission costs [$]. |
| $\nu_t$ | Fuel cost of thermal unit $t$ [$/MBtu]. |
| $\pi'_{y,s,\ell}$ | Contract price in $\ell sy$ [$/MWh]. |

### C. Variables

| | |
|---|---|
| $p_{y,s,\ell,h}$ | Power generation by hydro plant $h$ in $\ell sy$ [MW]. |
| $p_{y,s,\ell,t}$ | Power generation by thermal plant $t$ in $\ell sy$ [MW]. |
| $R_{y,s,h}$ | Hydro energy reserve of hydro plant $h$ at the beginning of $sy$ [MWh]. |

### D. Auxiliary Variables

| | |
|---|---|
| $g_{e,y,s,\ell}$ | Total power generation of firm $e$ in $\ell sy$ [MW]. |
| $\pi_{y,s,\ell}$ | Price of electricity in $\ell sy$ [$/MWh]. |

## II. INTRODUCTION

A GRACE period of energy surplus inherited from the previously expansive coordinated economics, better resource utilization [1], and available more efficient small power plants [2] tended the electricity industry in many countries to experience the deregulation. However, as energy demand increases due to economic growth, the challenge of providing new capacity surfaces. This new challenge is mainly due to shifting the generation expansion planning (GEP) from vertically integrated utilities to decentralized competitive firms [3], whose goals are to maximize their own profits. In the other words, the assumptions, models and methods of traditional least cost, reliability-oriented GEP are dramatically changed. However, the basic regulatory responsibility, i.e., long-term market stabilizing by providing required new generation resources, remains unchanged.

This paper proposes a comprehensive MADM framework that can be used by market regulators to select a suitable strategy, by which the social-economic market stability is better provided.

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MADM methods have been used in a variety of power system studies, especially in power system resource planning [4], [5], due to their capabilities in showing tradeoffs among different attributes and quantifying the preferences held by different interests.

As the main part of the proposed framework, the investment problem in the generation firms, we use a hybrid GA/Nash–Cournot model. In this model, a string as a GA population member represents the investment discrete decisions of the firms. Then, using the well-known Nash–Cournot Game theory to reflect the imperfect nature of real-world electric power markets simulates the interaction among firms in the short-term market. However, because Cournot models assume that rivals do not respond to price changes, the results are exquisitely sensitive to the elasticity and form of the market demand curve. As demand elasticity in power markets are now low, Cournot prices tend to be very high and uncertain [6]. A fuzzy inference system (FIS) is integrated in the model to incorporate the historical behavior of the market, and to impose an upper bound for the magnification of the simulated prices. Therefore, the FIS improves the reality of obtained results.

Finally, the framework is augmented by a tradeoff/risk analysis based on the developed concepts in [7], [8], as a supporting tool for decision-making under uncertainty. The risk analysis, as implemented here, requires a large database of possible future conditions and their effects on the regulator strategies. We use artificial neural networks (ANNs) to develop this required database by means of a few detailed evaluations.

The main attributes and contributions of this research can be summarized as: 1) classification of the regulator policies for the long-term market stabilization; 2) integration GA in a MADM framework makes it more flexible, such that various power markets can be evaluated easily by applying relevant modification in the short-term simulation part of the model; and 3) using a FIS in this simulation that provides the possibility of incorporating experts experiences and economical rules explicitly in the simulation procedure.

After this introduction, the main stages of the proposed MADM framework are discussed in Section III. Section IV is devoted to the short-term market simulation, and a case study is presented in the Section V. Section VI includes the main conclusions.

## III. MADM Framework

The main stages of the proposed framework are as follows:

1) initialization;
2) alternative determination;
3) market simulation;
4) utility analysis;
5) tradeoff/risk analysis.

The following subsections devoted to a brief discussion of these stages.

### A. Initialization

*1) Total Demand:* The planning horizon is divided to $Y$ years, each year to $S$ seasons and each season to $L$ load levels (group of hours with a similar demand level). In addition, it is assumed that the total demand in each load level is a linear function of the price in that load level (demand elasticity).

*2) Generation Units:* In the modeling of thermal generators, their rated power outputs, quadratic heat rate functions, capacity investment costs, and lifetimes are considered. The short-term constraints of thermal units, such as ramp rates and minimum up/down times are neglected in this long-term model, because these limitations have low impacts on expansion plans.

Hydro units are modeled considering their rated power outputs, reservoirs limited capacity, capacity investment costs, and lifetimes.

### B. Alternatives

In general, the possible strategies for market stabilization can be classified into three categories.

— *Supply entry:* A regulator can stabilize the electricity market by direct entry to the supply part of it as a nonprofit generation firm to provide required capacity. Constructing some base and/or peak load generation units and connecting to other networks are some examples for these strategies.

— *Market entry:* Such strategies as long-term contracting with the generators, limiting individual suppliers' market shares, controlling prices, and altering energy transaction structure of the market are categorized here. These strategies have a direct effect on the market structure and/or operation.

— *Demand entry:* Direct influencing the demand of energy can be selected by regulators to stabilize the long-term market. Various types of demand-side management (DSM) strategies, such as peak shaving and valley filling can be classified in this category.

After determination of possible strategies, all combinations of them are considered as the alternatives that should be evaluated from the market stability point of view. For example, if there are two market and three demand entry strategies for regulator, then six alternatives can be evaluated. Furthermore, the effect of each alternative on the input data must be determined. For example, if a 10% peak shaving is selected as a strategy, then the corresponding modifications should be applied to the total demand of the system for this strategy.

At the end of this stage, for each alternative a set of corresponding load and system data has been determined that will be used in the next stages.

### C. Market Simulation

In this part, for each alternative the expansion behavior of the generation firms is simulated by means of a hybrid GA/Cournot model. The main steps of the GA are as follows.

*1) Population Structure:* Each of the population members has a structure as

$$G = \lfloor G_{ye} \rfloor, \qquad y = 1, \ldots, Y \quad e = 1, \ldots, E \tag{1}$$

where each $G_{ye}$ has the form

$$G_{ye} = \lfloor cu_1 \quad \ldots \quad cu_m \quad \ldots \quad cu_{M_e} \rfloor. \tag{2}$$

Each $cu_m$ represents the number of type $m$ new candidate unit that in year $y$ owned by firm $e$. As an example, if $E = 3$, $M_e =$

2, and $Y = 5$, then the following matrix can show a population member:

$$\begin{bmatrix} \overbrace{0 \quad 0}^{e=1} & \overbrace{0 \quad 0}^{e=2} & \overbrace{0 \quad 0}^{e=3} \\ 1 \quad 0 & 1 \quad 1 & 2 \quad 1 \\ 3 \quad 3 & 2 \quad 2 & 2 \quad 1 \\ 3 \quad 3 & 2 \quad 2 & 2 \quad 1 \\ 3 \quad 3 & 2 \quad 2 & 2 \quad 3 \\ & & \end{bmatrix}.$$

This matrix represents that no new unit is added to system in the first year, but in the second year, firms #1, #2, and #3 construct 1, 2, and 3 new units, respectively. Also, in the fourth year, there is no addition to the system, and at the end of planning horizons 6, 4, and 5, new units would be owned by firms #1, #2, and #3, respectively. Finally, this matrix is reshaped as a string for other step calculations.

*2) Fitness Evaluation:* The fitness function of GA is a decentralized optimization problem itself that simulates the short-term behavior of the generation firms in the market. The main goal of the firms in this simulation is to maximize their own profits. The details of the problem structure are discussed later in Section IV.

After solving the short-term scheduling problems in each firm, the total profit of firms is calculated and the investment total costs are subtracted from it. Then, the final result is attached to each string as the fitness value of it.

*3) Selection, Crossover and Mutation:* At each iteration, the GA uses the current population to create the children that make up the next generation. The GA creates three types of children: Elite children are the individuals in the current generation with the best fitness values. These individuals automatically survive to the next generation. Combining the vectors of a pair of parents creates crossover children. Introducing random changes, or mutation, to a single parent, produces mutation children.

After some predetermined iteration, the best expansion plan; i.e., the plan with maximum total profit is determined for each alternative.

### D. Utility Analysis

The utility analysis is performed in three stages:

*1) Attributes Calculation:* For the long-term market stability assessment, we use five main attributes that are defined as follows.

— *Average price* ($x_1$): The average price of energy in the planning horizon, which is simulated.

— *Profit per energy unit* ($x_2$): This attribute is defined as the ratio of total profit of the market to the total generated energy in the planning horizon.

— *Competition improvement index* ($x_3$): The Herfindahl-Hirschman Index (HHI) is used for competition assessment of the market that is defined as

$$HHI = \sum_{e=1}^{E} s_e^2. \tag{3}$$

Thus, the HHI of 10 000 corresponds to a monopoly and for three firms with shares of 20%, 40%, and 40%; the HHI would be equal to 3600 $(400 + 1600 + 1600)$. Now, $x_3$ can be defined as

$$x_3 = \frac{(HHI_1 - HHI_2)}{HHI_1} \times 100$$

where $HHI_1$ and $HHI_2$ are the values of the HHI at the beginning and ending of the planning horizon, respectively.

Although it seems that the HHI is not an appropriate measure when large amounts of the power are traded on bilateral contracts, but the variation of its value, can provide a suitable perspective on the competition trend of the whole market.

— *Minimum annual capacity reserve* ($x_4$):

$$x_4 = \min_y \left( \frac{TG_y - PL_y}{TG_y} \times 100 \right).$$

— *Pollution index improvement* ($x_5$): We define the ratio of the clean generation capacity (hydro, nuclear, and so on) to the total capacity of the system as the pollution index (*PI*), therefore $x_5$ can be defined as

$$x_5 = \frac{(PI_1 - PI_2)}{PI_1} \times 100$$

where $PI_1$ and $PI_2$ are the values of the *PI* at the beginning and ending of the planning horizon, respectively.

*2) Composite Utility Function:* For transforming the $n$-dimensional attribute vector to a scalar performance measurement, the linear additive utility function is used. This model with its weaknesses/ strengths [9] has been used for a variety of decision problems in electric utility planning [10]. The general form of the model is

$$U(x) = \sum_{i=1}^{n} w_i U_i(x_i) \tag{4}$$

where $U(x)$ is the composite utility of each alternative; $x = [x_1 \quad \ldots \quad x_n]$ is the vector of attributes that represents an alternative; $w_i$ is a relevant importance factor for the $i$th attribute such that $\sum w_i = 1$; and $U_i(x_i)$ is the single utility function with respect to the $i$th attribute.

The single utility functions and the weighting parameters are the most important variables that must be determined. The single utility functions usually can be evaluated by the certainty equivalence method as described in [9]. However, such as many MADM applications, we use the normalized attribute value to represent these functions. This value is defined as

$$r_i = \left| \frac{x_i - x_i^*}{x_i^r} \right| \tag{5}$$

where $x_i^*$ is the optimal value of alternative $x_i$ and $x_i^r$ is the range of variation of measured attribute values.

Several methods are available for priority assessment or weighing-parameters selection in MADM analysis. In this paper, the ration-questioning method is selected. This method is often used with the technique of analytical hierarchy process (AHP) to break up the problem into several evaluation stages. The proposed hierarchy for generation expansion planning is shown in Fig. 1.

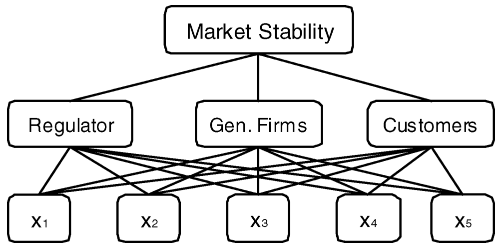


Fig. 1. Hierarchy for weighting-parameters selection.

In such a three-level hierarchy, each layer is only affected by the next nearest layer and the priority assessment of the attributes is done in two levels. Starting from the second layer, it will be asked from the decision maker to determine the relative importance of each pairs of players with respect to main goal in the first layer, i.e., the market stability. Then, the decision maker must estimate the relative priority of each pairs of the third layer attributes for each of the players in the second layer. This process results in judgment matrices for each layer, and finally priority vectors of these matrices can be calculated by means of the eigenvector method. The final priority vector of attributes is equal to the product of layer matrices.

*3) Imprecise Judgments:* To incorporate the effects of imprecise judgments, the method of [11] is used, in which the error variances of the judgment matrices can be estimated by

$$\sigma_{w_i}^2 = \frac{n^2-1}{n}\left[\sum_{i=1}^{n} w_i^2 - w_i^2\right]\sigma^2 w_i^2 \tag{6}$$

where

$$\sigma^2 = \frac{2}{(n-1)(n-2)}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} y_{ij}^2 \tag{7}$$

and $n$ is the judgment matrix size, $y_{ij} = Ln(a_{ij}/w_{ij})$, $a_{ij}$ is the judgment ratio for each attribute, and $w_{ij} = w_i/w_j$.

In addition, if we use the technique of the error propagation, we can calculate the variance of the composite utility function (5) as

$$\sigma_d^2 = \sum_{i=1}^{n} r_i^2 \sigma_{w_i}^2. \tag{8}$$

Finally, by assuming the normal distribution for the values of the composite distance, the likely range of its values can be estimated as

$$\left(U_d - \lambda_{\alpha/2}\sigma_d, U_d + \lambda_{\alpha/2}\sigma_d\right)$$

where $\lambda_{\alpha/2}$ represents a suitable confidence level.

On the base of these likely ranges, a number of alternatives are selected as the acceptable ones and the tradeoff/risk analysis is performed on them.

### *E. Tradeoff/Risk Analysis*

The basic concepts of tradeoff/risk analysis are presented in [12]. We use this method to estimate the robustness of the accepted alternatives against the uncertain future conditions. The main steps of tradeoff/risk analysis as performed in this paper are as follows.

*1) Scenario Development:* There are many uncertainties in power system planning procedure, especially in the competitive environments. Some of them are as follows:

— total peak demand;
— demand growth rate;
— price of energy;
— production costs;
— realization of the planned expansions;
— interest rates;
— economic growth;
— environmental conditions;
— regulation.

In this step, decision makers select the most important uncertainties and a range of possible variation is assigned to each of them. Then, these uncertainties are combined together and with alternatives to form a set of possible scenarios.

*2) Decision Data Expansion:* For each scenario, the values of attributes must be calculated in this step. However, this requires very computational efforts and it is a time-consuming step.

Some approximation methods are developed for reducing the volume of these computations. Describing function [13], high-order linear interpolation [14], and independent data analysis [15] are the most famous of these methods. The basic idea of these methods is to develop an approximate relation between attributes and decision variables. In the proposed framework, we use ANNs to develop this approximate relation between selected uncertainties and attributes. In other words, a back-propagation ANN is constructed for each alternative, trained and tested by some full-evaluated cases, and used to calculate the attributes for a wide range of uncertainties' variation.

*3) Robustness Assessment:* In this step, the acceptable alternatives are determined for each scenario, using the utility analysis (Section III-D). Finally, the alternatives are ranked, based on the following robustness index (*RI*):

$$RI = \frac{\text{No. of scenarios for which an alternative is acceptable}}{\text{Total number of scenarios}}. \tag{9}$$

## IV. SHORT-TERM MARKET SIMULATION

As in many works made in the electricity market analysis and operation, in this research the well-known Nash–Cournot model has been used for representing the market behavior. In this model, the competition occurs only in quantities, product is not storable and homogeneous, no entry occurs during the game, and decision-making by the players occurs simultaneously [16]. With the starting of the game, each player chooses the level of its production to maximize its profit, and assumes that the production of the other players will not change. Outcomes of Cournot games are called Nash equilibria. Nash equilibria are vectors of output quantities that maximize the profit of each player given all other firms' quantity decisions. Therefore, in the modeling

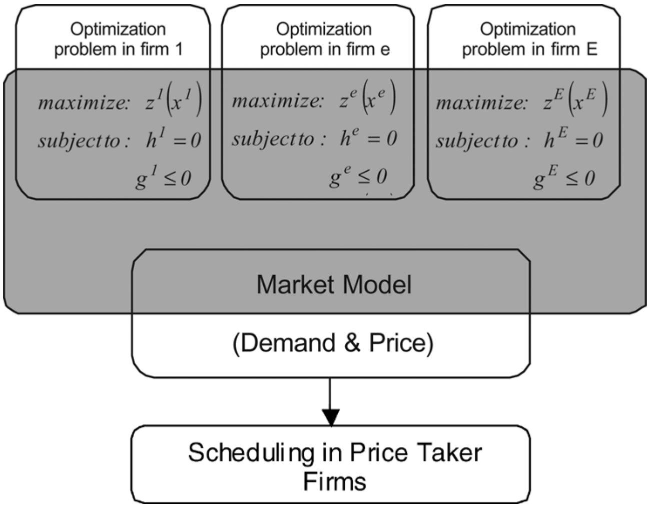


Fig. 2. Market structure.

of this type of market, the problem of profit maximization must be considered simultaneously.

The main structure of the proposed model is shown in Fig. 2, where $z$ represents the profit of each firm $e \in [1, \cdots, E]$ (revenues–operation costs), $x$ represents the decision variable (power output of each unit owned by firm $e$) and the sets of constraints $h$ and $g$ represent the technical, financial and other limits. A simple FIS and an elasticity relation between price and demand model the link among all optimization problems, the electricity market.

It should be noted that we distinguish between price makers and price takers, because the price makers are the main players of oligopolistic markets. They have the potential to exercise the market power and are able to influence prices to their own profits.

After reaching the Nash equilibrium, setting the outputs of price-maker firms, and determining the market price, the scheduling problem in the price taker firms would be solved for the rest of demand and base on the equilibrium prices of energy.

The detailed implementation procedure is shown in Fig. 3.

The following subsections are devoted to a brief discussion about the main items of this figure.

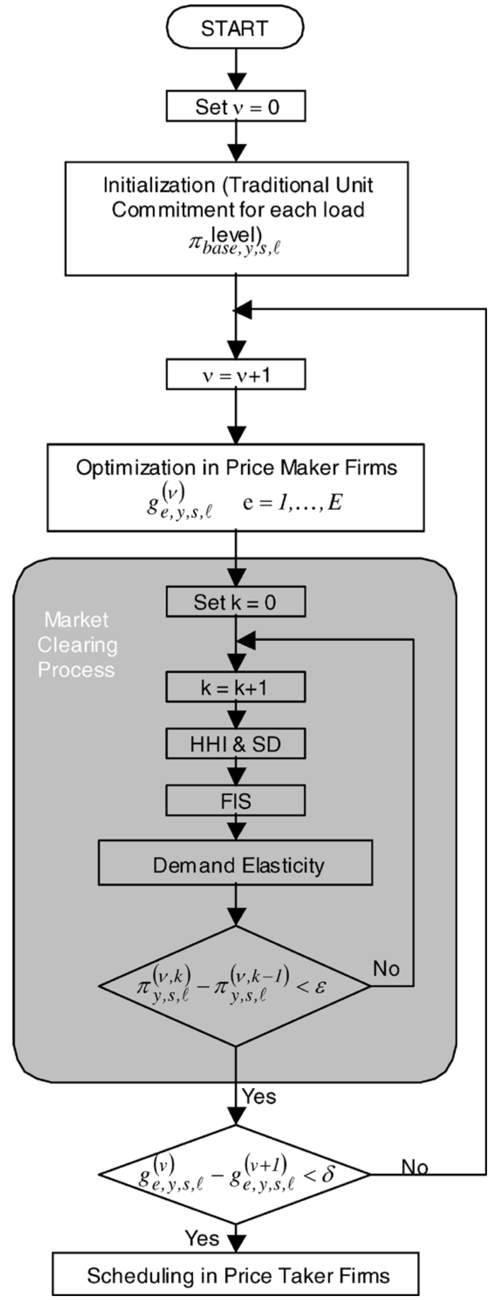


Fig. 3. Detailed implementation procedure.

## *A. Initialization*

Here, after reading the required data, a traditional unit commitment is performed to calculate the marginal cost in each of the load levels of the system ($\pi_{base}$). Then, the basic market price in each load level is set equal to $\pi_{\mathrm{base}}$. The effects of the fuel price as the most important factor is reflected in the $\pi_{\mathrm{base}}$.

## *B. Optimization in Price-Maker Firms*

In this step, each firm plans its generation schedule. This planning process is an optimization problem in which the goal is maximizing the profit of firm; the inputs are the technical information of generation units, the price of energy, and the demand; and the outputs are the generation levels of the firm units that would be supplied to energy market. In fact, this problem is a profit-based economic dispatch as follows:

$$\begin{aligned}\mathrm{Max}\quad & \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{\ell=1}^{L} d_{y,s,\ell}\left(g_{e,y,s,\ell} - q_{y,s,\ell}\right)\pi_{y,s,\ell} \\ & + \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{\ell=1}^{L} d_{y,s,\ell} q_{y,s,\ell}\pi'_{y,s,\ell} \\ & - \sum_{y=1}^{Y}\sum_{s=1}^{S}\sum_{\ell=1}^{L} d_{y,s,\ell}\sum_{t=1}^{N_t}\nu_t H_t(p_{y,s,\ell,t}) - \sum_{y=1}^{Y} t_y TR_y \qquad (10)\end{aligned}$$

$$\mathrm{S.T}: \quad \sum_{\ell=1}^{L} d_{y,s,\ell}\, p_{y,s,\ell,h} - R_{y,s,h} + R_{y,s+1,h} - A_{y,s,h} \le 0 \qquad (11)$$

$$\underline{R}_h \leq R_{y,s,h} \leq \overline{R}_h \quad (12)$$
$$\underline{p}_h \leq p_{y,s,\ell,h} \leq \overline{p}_h \quad (13)$$
$$\underline{p}_t \leq p_{y,s,\ell,t} \leq \overline{p}_t \quad (14)$$
$$g_{e,y,s,\ell} = \sum_{t=1}^{N_t} p_{y,s,\ell,t} + \sum_{h=1}^{N_h} p_{y,s,\ell,h} \leq D_{y,s,\ell}. \quad (15)$$

The objective function (10) represents the profit of the firm in the planning horizon. The constraints (11) show that the hydro inflows in and the initial and final reservoir levels in each season limit the available energy of hydro units. The constraints (12)–(14) are the variable bounds and (15) represents the demand constraints.

Some other local limitations can be added to this optimization problem. For instance, environmental factors can be added as a cost (e.g., $SO_2$ adder) or a constraint (e.g., thermal emission to water).

### C. Market Clearing Process

Three main stages of this part are as follows:

*1) HHI and SD Calculations:* Generally, the first step in assessing a market's competitiveness is to evaluate the market structure, usually market shares of suppliers, since market power is inherently a problem tightly related to structure [17]. HHI as defined in (3) addresses this issue. Although, the HHI has no supporting theory but it is used widely because it gives proportionately greater weight to the market share of a large supplier and takes into account all supplier in the market [17].

SD simply represents the supply/demand relation, and is defined as the percent of demand that is not met by suppliers; i.e., in each load level

$$SD_{y,s,\ell} = \frac{\sum_{e=1}^{E} g_{e,y,s,\ell} - D_{y,s,\ell}}{D_{y,s,\ell}} \times 100. \quad (16)$$

It should be noted that in the market clearing process, the HHI and SD act as dynamic variables. In other words, the values of them are recalculated in each of the process iterations by means of new generation levels of the firms and total demand of the system.

*2) FIS:* The structure of FIS is shown in Fig. 4. The shape and limits of the membership functions must be selected on the base of expert experiences or historical data of the system.

The five simple rules regulate the developed FIS and are as follows:

— If (SD is Low) then (K is High).
— If (SD is High) then (K is Low).
— If (SD is Adequate) AND (HHI is Low) then (K is Low).
— If (SD is Adequate) AND (HHI is Moderate) then (K is Moderate).
— If (SD is Adequate) AND (HHI is High) then (K is Not Low).

The first (second) rule shows that if the devoted capacity to the market by price makers is much less (more) than the demand, then the magnification of the price is high (low) [18]. The last three rules represent the effect of the market competition structure on the prices.

In a competitive market, the supply/demand relation is the most important economical factor that determines the price [18].

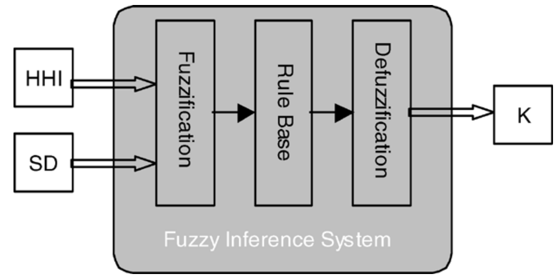


Fig. 4. Structure of the FIS.

TABLE I
TYPE AND NUMBER OF UNITS OWNED BY FIRMS

| | Generation Firm | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| U12 | 2 | 1 | 2 | - | - | - | - | - | - | - |
| U50 | - | 6 | - | - | - | - | - | - | - | - |
| U76 | 2 | 3 | 2 | - | - | - | - | - | - | - |
| U100 | 2 | 3 | 2 | - | - | - | - | - | - | - |
| U155 | 2 | 1 | 1 | 1 | 1 | - | - | - | - | - |
| U197 | 2 | 3 | 2 | - | - | 1 | 1 | - | - | - |
| U350 | 3 | 1 | 1 | - | - | - | - | 1 | 1 | - |
| U400 | 6 | 1 | 1 | - | - | - | - | - | - | 1 |
| Total | 19 | 19 | 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

TABLE II
NEW CANDIDATE PLANTS

| Type | U-I | U-II | U-III |
|---|---|---|---|
| Size [MW] | 100 | 200 | 500 |
| Cap. Cost [$/kW] | 800 | 1060 | 1200 |
| Avg. Energy Cost [$/MWh] | 35 | 15 | 7.5 |
| Life Time [Yr.] | 30 | 30 | 40 |

Thus the effect of SD in the above rules is more than the effect of HHI.

The output of the FIS, $K$, on the analogy of the conduct parameter [19], is considered as the magnification factor of the price with respect to the base price; that is, the final price in each load level is set to

$$\pi = K \cdot \pi_{\text{base}}. \quad (17)$$

It should be noted that the parameter $K$ is estimated for some real life systems, e.g., in the California market, $K$ is estimated between 1.15–1.99 [20] and in the U.K. it is about 1.25 [21].

*3) Load Elasticity:* After determining $\pi$, the total demand of the system is modified through the following elasticity equation:

$$D_{y,s,\ell} = -a_{y,s,\ell}\pi_{y,s,\ell} + b_{y,s,\ell}. \quad (18)$$

Then, steps 2 and 3 are repeated until the convergence.

Finally, it should be noted that in the markets with locational marginal pricing regime, the final obtained prices by this simulation, could be treated as the generation components of locational marginal prices (LMPs), and then augmented by two other LMP components (the marginal price of transmission losses and the marginal price of the network constraints that are enforced in power flow model). An insightful discussion on LMP decomposition using load distribution factors is found in [22] and in [23], it is proven that the LMP can be decomposed into three components and also a calculation method is developed.

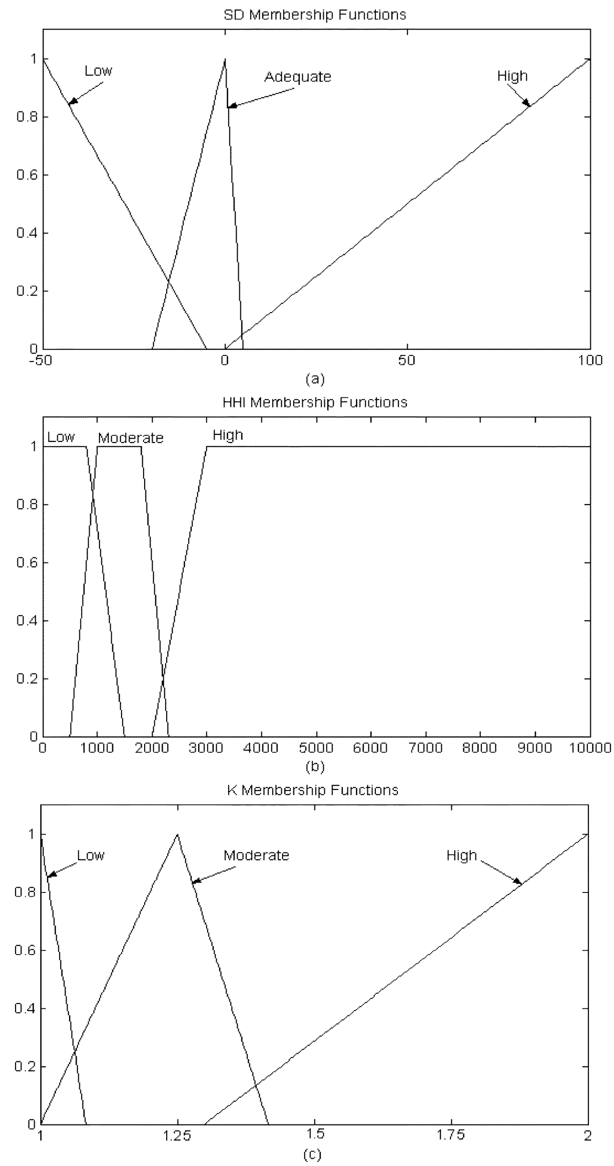


Fig. 5. Selected membership functions for FIS.

TABLE III
JUDGMENT MATRICES

| Judgment Matrices and Priority Vectors: | | | | | | |
|---|---|---|---|---|---|---|
| Level 2.1: | The Market Stability Objective | | | | | Priorities |
| Regulator | 1 | 1 | 2 | | | 0.4000 |
| Gen. Firms: | 1 | 1 | 2 | | | 0.4000 |
| Customers | ½ | ½ | 1 | | | 0.2000 |
| Level 3.1: | Regulator | | | | | |
| $x_1$ | 1 | 1 | ½ | 2/9 | 1 | 0.10526 |
| $x_2$ | 1 | 1 | ½ | 2/9 | 1 | 0.10526 |
| $x_3$ | 2 | 2 | 1 | 4/9 | 2 | 0.21053 |
| $x_4$ | 9/2 | 9/2 | 9/4 | 1 | 9/2 | 0.47368 |
| $x_5$ | 1 | 1 | ½ | 2/9 | 1 | 0.10526 |
| Level 3.2: | Generation Firms | | | | | |
| $x_1$ | 1 | 1/9 | 1/3 | 1/3 | 1/3 | 0.05263 |
| $x_2$ | 9 | 1 | 3 | 3 | 3 | 0.47368 |
| $x_3$ | 3 | 1/3 | 1 | 1 | 1 | 0.15789 |
| $x_4$ | 3 | 1/3 | 1 | 1 | 1 | 0.15789 |
| $x_5$ | 3 | 1/3 | 1 | 1 | 1 | 0.15789 |
| Level 3.3: | Customers | | | | | |
| $x_1$ | 1 | 9 | 3 | 3 | 9/5 | 0.42857 |
| $x_2$ | 1/9 | 1 | 1/3 | 1/3 | 1/5 | 0.04762 |
| $x_3$ | 1/3 | 3 | 1 | 1 | 3/5 | 0.14286 |
| $x_4$ | 1/3 | 3 | 1 | 1 | 3/5 | 0.14286 |
| $x_5$ | 5/9 | 5 | 5/3 | 5/3 | 1 | 0.23810 |
| Final Priority: Market Stability Objective | | | | | | |
| $x_1$ | 0.14887 | | | | | |
| $x_2$ | 0.24110 | | | | | |
| $x_3$ | 0.17594 | | | | | |
| $x_4$ | 0.28120 | | | | | |
| $x_5$ | 0.15288 | | | | | |

## V. CASE STUDY

### A. System and Market

The proposed method has been tested using a realistic power system. The demand and unit data are selected from 1996 IEEE-RTS [24]. The planning horizon is five years, each year has four hydro seasons and each season has ten load levels. The peak demand at the beginning of the planning horizon is 8750 MW, the total installed capacity is 10 345 MW, the demand growth rate is 7.2% and the discount rate is 5%.

The market includes three price-maker generation firms owning 19, 19, and 11 units and seven single-unit price-taker firms. The distribution of units among firms is shown in Table I.

Table II represents the specifications of new candidate units. It is assumed that each price-maker firm can construct seven new plants with a total capacity of 1400 ($3\times100+3\times200+500$) MW, but each price-taker firm can construct only one of the types U-I or U-II new plants ($1 \times 100$ or $1 \times 200$ MW), in the planning horizon.

### B. Regulator Strategies

The following strategies can be applied to the market by regulator.

— Supply entry:
- G1. No supply entry
- G2. Constructing a 400 MW nuclear power plant
- G3. Constructing $6 \times 50$ MW hydro units

— Market entry:
- M1. No market entry
- M2. Prepurshasing 10% of present installed capacity with a 25 $/MWh constant price
- M3. Prepurshasing 20% of new installed capacity with a 25 $/MWh constant price

— Demand entry:
- D1. No demand entry
- D2. 10% peak demand shaving
- D3. A DSM program with 5% peak demand shaving and 10% off-peak demand increasing.

Therefore, a total number of 27 alternatives should be evaluated.

### C. Market Simulation

*1) GA Specifications:*

- population size: 25;
- initialization: with zero as one of the first population;
- elitism: 15% of population;
- crossover rate: 0.85 (stochastic three points crossover);
- mutation rate: 0.025 per gene.

TABLE IV
ALTERNATIVES AND THEIR UTILITY VALUES

| No. | Alternative Description | $x_1$ [\$/MWh] | $x_2$ [\$/MWh] | $x_3$ [%] | $x_4$ [%] | $x_5$ [%] | Point Estimate | Likely Range | | Ranking |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Low | High | |
| 01 | [G1 M1 D1] | 39.03 | 10.14 | -1.9493 | 15.9297 | 4.2113 | 0.60324 | 0.54770 | 0.65879 | **22** |
| 02 | [G1 M1 D2] | 42.97 | 13.80 | -0.3612 | 23.7822 | 4.9751 | 0.35191 | 0.30116 | 0.40267 | **1** |
| 03 | [G1 M1 D3] | 40.80 | 11.74 | -0.3612 | 19.3210 | 4.9751 | 0.48167 | 0.43249 | 0.53085 | **12** |
| 04 | [G1 M2 D1] | 33.62 | 11.45 | -2.0582 | 4.8542 | -3.9005 | 0.67320 | 0.61160 | 0.73480 | **26** |
| 05 | [G1 M2 D2] | 33.92 | 10.91 | 2.0763 | 19.6608 | 10.6516 | 0.36095 | 0.32620 | 0.39570 | **2** |
| 06 | [G1 M2 D3] | 31.43 | 9.11 | -4.9466 | 14.2706 | 1.1877 | 0.63153 | 0.56984 | 0.69322 | **23** |
| 07 | [G1 M3 D1] | 36.26 | 10.21 | -3.8073 | 10.7342 | 0.4061 | 0.67914 | 0.61872 | 0.73955 | **27** |
| 08 | [G1 M3 D2] | 40.24 | 12.67 | -3.0277 | 25.0567 | 1.2644 | 0.41105 | 0.35932 | 0.46278 | **7** |
| 09 | [G1 M3 D3] | 40.05 | 11.88 | -0.2534 | 16.5348 | 4.2113 | 0.50556 | 0.45669 | 0.55444 | **15** |
| 10 | [G2 M1 D1] | 40.18 | 11.60 | 9.9821 | 8.6164 | -0.3636 | 0.54513 | 0.49292 | 0.59734 | **19** |
| 11 | [G2 M1 D2] | 38.48 | 11.31 | 1.1353 | 18.4001 | -1.1216 | 0.51246 | 0.46317 | 0.56175 | **16** |
| 12 | [G2 M1 D3] | 39.60 | 11.31 | 8.6351 | 15.1975 | 7.3349 | 0.42535 | 0.38484 | 0.46586 | **9** |
| 13 | [G2 M2 D1] | 33.12 | 9.09 | 5.3705 | 16.5370 | 0.5535 | 0.51759 | 0.46828 | 0.56689 | **18** |
| 14 | [G2 M2 D2] | 34.84 | 12.47 | 11.2086 | 13.7269 | -6.9647 | 0.40237 | 0.35660 | 0.44814 | **6** |
| 15 | [G2 M2 D3] | 35.73 | 13.06 | 6.2457 | 15.7991 | -3.3279 | 0.38614 | 0.34567 | 0.42660 | **5** |
| 16 | [G2 M3 D1] | 39.88 | 11.93 | 7.5688 | 4.1410 | -7.7004 | 0.66213 | 0.59829 | 0.72596 | **24** |
| 17 | [G2 M3 D2] | 39.27 | 12.04 | 7.0843 | 15.0681 | -7.7004 | 0.51350 | 0.45996 | 0.56705 | **17** |
| 18 | [G2 M3 D3] | 40.64 | 12.67 | 9.5411 | 8.0981 | -5.4574 | 0.54725 | 0.49037 | 0.60413 | **20** |
| 19 | [G3 M1 D1] | 38.85 | 10.66 | 6.4428 | 3.2611 | 1.8134 | 0.66540 | 0.60720 | 0.72361 | **25** |
| 20 | [G3 M1 D2] | 39.26 | 10.95 | 2.9334 | 19.4569 | 9.2063 | 0.43167 | 0.38946 | 0.47387 | **10** |
| 21 | [G3 M1 D3] | 37.44 | 8.85 | 5.7348 | 15.8476 | 13.2980 | 0.49704 | 0.44796 | 0.54611 | **14** |
| 22 | [G3 M2 D1] | 35.92 | 12.54 | 4.0726 | 12.0924 | 12.4553 | 0.37029 | 0.33591 | 0.40467 | **3** |
| 23 | [G3 M2 D2] | 33.07 | 11.67 | 8.5162 | 7.5152 | 7.9866 | 0.41928 | 0.38111 | 0.45744 | **8** |
| 24 | [G3 M2 D3] | 35.80 | 13.09 | 3.9148 | 11.0759 | 9.0813 | 0.38147 | 0.34592 | 0.41703 | **4** |
| 25 | [G3 M3 D1] | 40.89 | 12.86 | 2.5267 | 9.7585 | 10.8070 | 0.47779 | 0.42969 | 0.52589 | **11** |
| 26 | [G3 M3 D2] | 40.97 | 13.32 | 0.5922 | 15.7561 | -1.4073 | 0.48918 | 0.43660 | 0.54177 | **13** |
| 27 | [G3 M3 D3] | 39.78 | 12.45 | 2.5151 | 10.3496 | -0.6214 | 0.55922 | 0.50686 | 0.61159 | **21** |

*2) FIS Tuning:* As previously stated, the FIS can be tuned either by observing the historical trend of prices, or by using the expert experiences. Since the capacity owned by price-takers is about 20% of total installed capacity of the system, if at least 80% of the demand could be met by price-makers ($\mathrm{SD} > -20$), then the price magnification due to SD is not considerably high. On the other hand, if there is only a 5% supply surplus, it can be assumed that the effect of SD on the prices is fairly low. Therefore, the membership functions of SD are selected as in Fig. 5(a).

We choose the limits of membership functions of HHI base on the FERC and Department Of Justice (DOJ) experiences, that is the market is considered unconcentrated if $\mathrm{HHI} < 1000$, moderately concentrated if $1000 < \mathrm{HHI} < 1800$ and highly concentrated if $\mathrm{HHI} > 1800$ [25]. Based on these data, the HHI membership functions are chosen as in Fig. 5(b).

The output membership functions of FIS are presented in Fig. 5(c), because it is assumed that the magnification of prices in this system would not be greater than 2.

Other settings of FIS are as follows:

- and method: product;
- or method: probabilistic or;
- implication: min;
- aggregation: max;
- defuzzification: centroid of area method.

## D. Utility Analysis

Table III shows the judgment matrices that are used together with the AHP of Fig. 1 to estimate the composite utility values for alternatives.

The values of selected attributes are presented in Table IV for all of the alternatives. Also, the point and likely range estimates of composite utility are shown there. In likely range calculations, by using a 95% confidence level, we assume that $\sigma_{w_i} = 0.02$.

Fig. 6 represents the likely range utility values. Each alternative, which its utility value lays on the dark band, can be considered as an acceptable alternative. Therefore, ten alternatives (ranking from 1–10 in Table IV) are selected for tradeoff/risk analysis in the next stage.

## E. Tradeoff/Risk Analysis

*1) Organization:* In this case, three uncertainties are modeled: demand growth rate (DGR), production costs (PRC), and new capacity realization (NCR). Table V represents the assumed boundaries for these parameters together with the steps of their variations. The base case is the evaluated main case in the previous sections.

*2) Data Base Expansion:* The following steps are performed for each acceptable alternative.

- 46 boundary scenarios were developed and evaluated by applying the proposed market simulation method.
- An ANN is trained and tested by these detailed scenarios. For example, the performance of the developed ANN for alternative #2 is shown in **Fig. 7**.
- The values of attributes are calculated for all 40375 scenarios by means of trained ANNs.

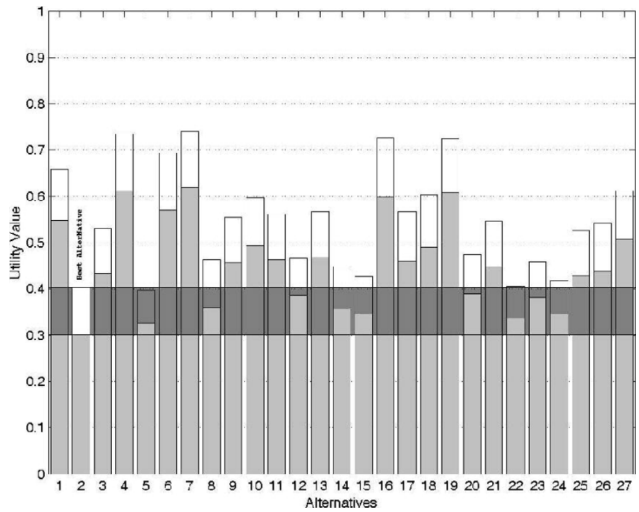


Fig. 6. Acceptable alternatives.

TABLE V
UNCERTAIN PARAMETERS

| Uncertainty | DGR | PRC | NCR |
|---|---|---|---|
| Lower Boundary | 5.2% | 80% | 12.5% |
| Base Case | 7.2% | 100% | 100% |
| Upper Boundary | 9.2% | 125% | 100% |
| Variation Step | 0.5% | 5% | 6.25% |

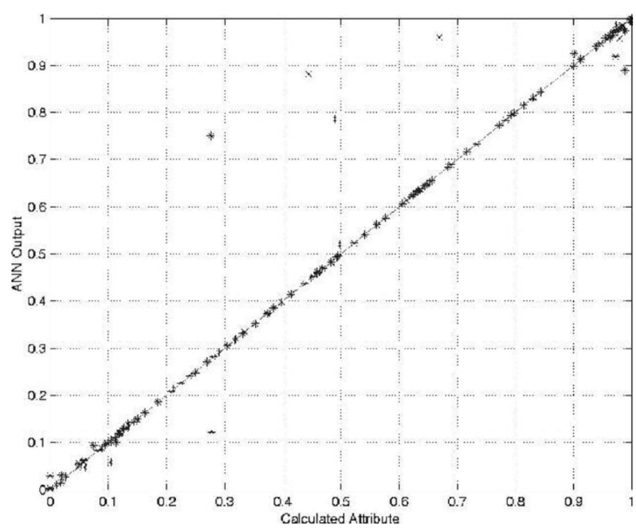


Fig. 7. Performance of a sample ANN.

Then, for each scenario the utility analysis of Section V-D is repeated and the acceptable alternatives are determined.

Finally, The RI as defined in (9) is calculated for each alternative. The results are represented in Table VI.

### *F. Results*

The obtained results from the case study are summarized as follows.

If the regulator selects G1 or "No supply entry" as his/her strategy, then all three acceptable alternatives have D2 as their demand entry strategy. However, in this condition, the M1 or "No market entry" is the best strategy for uncertain futures.

TABLE VI
TRADEOFF/RISK ANALYSIS RESULTS

| No. | Utility Ranking | Alternative Description | RI [%] | RI Ranking |
|---|---|---|---|---|
| 02 | 1 | [G1 M1 D2] | 43.72 | 4 |
| 05 | 2 | [G1 M2 D2] | 35.61 | 8 |
| 22 | 3 | [G3 M2 D1] | 38.79 | 7 |
| 24 | 4 | [G3 M2 D3] | 32.95 | 10 |
| 15 | 5 | [G2 M2 D3] | 35.08 | 9 |
| 14 | 6 | [G2 M2 D2] | 44.28 | 3 |
| 08 | 7 | [G1 M3 D2] | 39.12 | 6 |
| 23 | 8 | [G3 M2 D2] | 46.74 | 1 |
| 12 | 9 | [G2 M1 D3] | 44.90 | 2 |
| 20 | 10 | [G3 M1 D2] | 41.24 | 5 |

Selection of G2 means that the combination [M2 D3] is out of order. But, selection of [M2 D2] will have a good effect on the robustness of the system.

The M2 and D2 are the most frequent strategies in the acceptable alternatives. Therefore, if the regulator selects them, then the comparison between alternatives #05, #14, and #23 shows that the G3 is the most robust and G2 is the most useful strategy. In the other words, construction of a 400-MW base-load plant will improve the market stability, but if regulator constructs $6 \times 50$ MW hydro units, the flexibility and robustness of the system against uncertain futures will be better. In these conditions, the generation entry by regulator is essential because, G1 is not a suitable policy.

Comparison of alternatives #02, #12, and #20, in which the regulator not enter the market, shows that the "No market entry" increases the pressures on the customers. For these alternatives, the average prices $x_1$ are higher than the others.

Although, in a general view, it seems that the alternative #02 is the best, but it should be noted that this alternative, applies the highest limitations on the customers. The customers, not only should pay the highest prices, but also must experience a 10% peak demand shaving.

If the selected demand entry strategy is D1, i.e., "No demand entry", then alternative #22 is the only acceptable one. This alternative has a fairly suitable utility and a considerable robustness.

Generally, the four alternatives #02, #14, #22, and #23 may be offered to final decision makers as the better ones. Best alternative selection by decision makers is highly dependent to other criteria such as financial capabilities of the regulator, customer importance in the decision-makers point of view and other socio-political conditions.

## VI. CONCLUSION

This paper presented a comprehensive MADM framework for long-term market stability evaluation by the regulator entity of the market, in which a game-theoretic model was used to simulate the oligopolistic behavior of the short-term market, by means of a fuzzy inference system that can be tuned by observing the historical trend of prices. Then, this simulation tool is involved in a genetic algorithm to model the long-term investment decisions of the generation firms who try to maximize their profits. To support the framework against uncertain future conditions, a tradeoff/risk analysis is performed in which, the required database was expanded by means of the artificial neural networks. Although applying the proposed framework requires large computational efforts and it is a time-consuming process, this situation is natural in solving such large complex problems.

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