Wind Power, Distributed Generation: New Challenges, New Solutions

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***Abstract* — This paper discusses some issues related with the growing importance of wind power and distributed generation in modern power systems, and presents some solutions obtained with application to real cases.**

***Index Terms* – Wind generation, distributed generation, computational intelligence**

I. Introduction

DISTRIBUTED generation is assuming an important role in modern power systems. The progress in technologies has allowed that a portfolio of solutions may now be considered and found profitable, while only a few years ago one would witness arguments stating that only large centralized power stations would lead to economic feasibility.

The most widespread distributed generation alternatives are: mini-hydros, wind generation, co-generation (CHP, combined heat and power) in industry or buildings, and small independent power generators (diesel, gas or biomass).

Wind generation, in particular, has placed new challenges to system operation and planning, because of the "undispatchable" nature of wind, the difficulty in forecasting and the impossibility to store it.

The emergence of distributed generation is coupled with the restructuring of the electric sector and the market orientation it received in recent years. This has opened business opportunities to private investors, non institutional, in supplying power to the grid, resulting in a new inflow of capital to the sector, coming from sectors that traditionally were not investing in the energy business.

This has also presented new problems to an industry that was used to a tight control of their supply system. Suddenly, not only planning became a difficult exercise, because the existence and location of new power plants became uncertain and depending on the decisions of third parties, but also the operation became confronted with new degrees of uncertainty, not only as a result of private operators but also as a function of wind unpredictability.

The traditional tools, at many levels, used to assist engineers and decision makers in planning and operation became obsolete, at least while they could not cope with the new problems. At the same time, one has witnessed the progressive acceptance by the industry of new paradigms for reaching solutions and conclusions, which are progressively being integrated in the EMS/DMS environments, as well as being progressively accepted as useful means to provide the answers the new problems require.

In this paper we will review some problems raised by the emergence of distributed generation, and how computational intelligence and other modern techniques have been able to provide valuable results in solving the new problems. The objective is to raise, both in academia and in the industry, the interest and confidence in these tools by demonstrating how useful they are now becoming.

We will discuss briefly, in the following sections, the following topics:

- Spatial load forecasting – and how a combination of GIS (Geographical Information Systems) with Fuzzy Inference Systems and cellular automata allows forecasts of load evolution in a territory
- Energy resource evaluation – and how GIS models allow one to recognize and value, in a territory, the best technologies to assure power supply
- Construction of wind parks, and how a combination of Fuzzy Logic with GIS (Geographical Information Systems) may help in assessing visual impacts
- Investments in wind generation – and how a Negotiation Aid System, based on GIS and Fuzzy Logic may help in identifying geographical areas with less potential risk of conflict between investors and environmentalists
- Wind power prediction – and how new fuzzy-neural models, assisted by evolutionary methods, allow one to predict the power production of a wind park
- EMS for isolated systems with high penetration of wind production – and how new models were developed to take in account, in unit commitment and generation dispatch, wind penetration and dynamic security constraints
- Operation of distribution networks – and how using evolutionary methods one may take advantage of the existence of distributed generation in distribution networks
- Expansion planning of power systems – and how one must deal with uncertainty in systems with large penetration of renewables.

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These topics are just demonstrative of the new challenges and the new solutions available – by no means do they cover all kinds of problems that one is facing presently. They are all results from the work developed for more than 15 years at INESC Porto and, in a majority of cases, they have had application in real world cases. They will not be discussed extensively but only used as examples, and the reader may obtain more information from consulting the references provided at the end of the paper.

II. Spatial load forecasting

Distribution planning differs from generation/transmission planning in the fact that spatial uncertainty becomes much more relevant in conditioning investments. Therefore, models based on GIS – Geographical Information Systems, are the best suited for the task.

Spatial Load Forecasting (SLF) aims at not only establishing a prediction of load growth but also at defining the geographical location of the relative growths. The original works on Spatial Load Forecasting were developed by Willis [1] and gave place to some industrial computer applications, Later, a model that combined the features of GIS with Computational Intelligence tools emerged [2], with the name of Fuzzy Spatial Load Forecasting (FSLF).

The basic idea behind the FSLF approach is to learn, form maps of the past development of a territory, the implicit or hidden rules that govern, in a territory, the evolution of energy demand. These rules are organized in the form of a Takagi-Sugeno Fuzzy Inference System (TS-FIS) and, under the assumption that human behavior will not experience drastic changes, they may be applied to a map or a territory, to predict the future demand. In this approach, the functions that relate saturation of a territory cell and its derivative or PfD (Potential for Development) are established by rules in a fuzzy inference engine. These functions are represented as a set of thousands of fuzzy rules.

Here's one example of a rule:

IF *(distance to road is CLOSE)* ***AND***
(distance to urban center is MODERATE CLOSE) ***AND***
(terrain slope is MODERATE) ***AND***
(domestic saturation is MEDIUM) ***AND***
(industrial saturation is LOW)
THEN
Domestic PfD is 20 consumers per stage per km^2 ***AND***
Industrial PfD is 0.1 consumers per stage per km^2

These rules are automatically generated in a learning process that uses past maps as training data. Each cell in a map is a location with a given set of properties and a certain load and during the training phase the weights governing each rule are progressively tuned. The method of tuning depends on the type of TS-FIS used. In the first model, a 0-order was used.

The rules depend on the number of influence factors identified. After the training process, they are then stored in the GIS database and are used as in a lookup table in the process. This training process captures the basic behavior of demand development in a region, assuming that the human, social and economic behavior will not change noticeably along time.

Figure 1 presents an illustration of the application of the Fuzzy Inference System to a geographic region (island of Santiago, Cape Verde Republic, Africa). The example considers three influencing factors conditioning demand development.

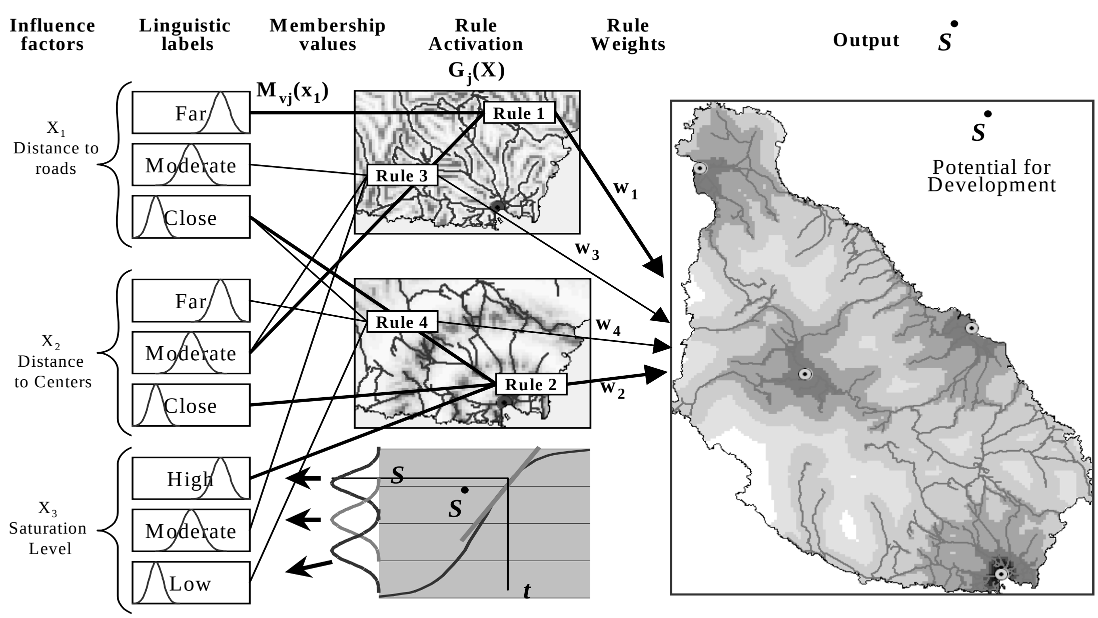

Figure 1 - Illustration of the fuzzy inference process - on each map location, membership functions are activated by input values for 3 influence factors; several layers of rule zones are mapped; the weights of rules are applied to each case and a map of PdF is generated for each consumer class - the darkest zones in the map on the right represent the zones with higher PdF (near centers and near roads).

Maps of potential for development are associated to continuous variables, and cellular automata are then applied to generate maps of actual demand, in an iterative process that may span over several years. In Figure 2 one may see maps of forecasted number of residential consumers at distinct time stages in a simulation applied to Cape Verde.

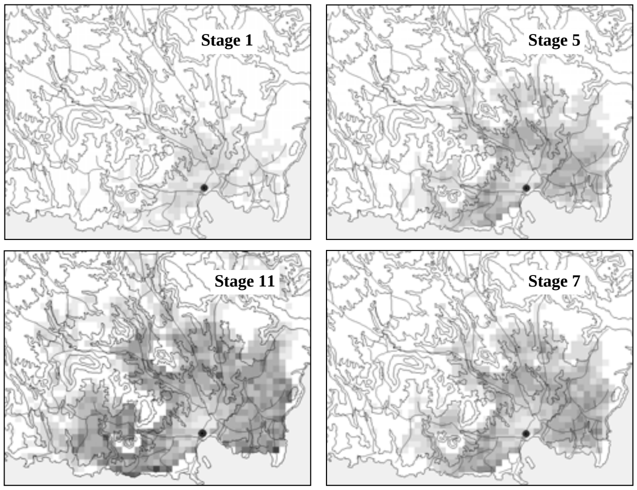

Figure 2 – Maps of forecasted number of consumers (of domestic type) after the action of the cellular automata, in a dynamic process of forecasting load growth along 11 time stages.

The geographical inputs (influence factors), are the following:

- Distance to main urban centers (4 linguistic labels)
- Distance to secondary urban centers (4 linguistic labels)
- Saturation Level (6 linguistic labels)
- Distance to roads (5 linguistic labels)
- Distance to coast line (3 linguistic labels)
- Terrain slope (4 linguistic labels)

Linguistic labels associated with fuzzy membership functions reclassify the influence factor values (e.g. distance to roads between 0 and 2 km: VERY CLOSE; distance to roads between 1 and 3 km: MODERATE CLOSE).

The study region had 2400 km^2 including one main urban center and three secondary centers. The resolution on GIS spatial analysis was 250m which meant cell based maps with 38400 cells. The historical growth was based on the geographical building growth along the last 30 years.

III. Energy Resource Evaluation

Endogenous energy resources in a territory include wind, hydro, biomass, solar. To supply electricity to local consumption, they must compete among themselves and against the natural expansion of an interconnected grid. Also, they may contribute to the power injection in the grid.

The evaluation of resource potential is a necessary step, but is not enough: one must assess not energy potential, but use feasibility. Therefore, one must evaluate the competition between different technologies, in order to understand which one, for each location, each use and each demand magnitude, is the most favorable option – taking in account a set of criteria including cost, reliability, security of supply.

A number of projects have been developed implementing resource survey and competition among technologies, for a diversity of regions in the world. One of the first has been the project SOLARGIS [3], in the JOULE programme of the EU 4th Framework. Later, a project called MEAPA was developed for a zone in the Amazon region in Brazil. And more recently, yet another project named ENERGIS has been designed for the region of La Rioja, Spain [4].

The main purpose of this GIS-based methodology is to provide answers to questions associated with a developing region, such as: what is the best system/technology for each place, what are the best places for a given technology, what is the cost of electricity from each technology, what is the potential market for each technology, what is the best electrification plan for a region.

A certain number of phases must be followed:

- Mapping the endogenous energy resources (wind, solar, biomass, hydro). Several models may be used for this purpose, coupled with the available information collected from a number of sources (meteorological data, airports, agricultural departments, etc.).
- Mapping transportation costs – from each possible supply point to each location in the map. Transportation of equipment may represent an important fraction of the total cost of using a given technology – like transporting wind generators, or diesel engines – because of the means necessary to employ for remote locations. Also, the transportation of technicians for repair or maintenance must be taken in account. Special modules allow the automatic generation of transportation paths in a map and associate them with a cost data base.
- Calculating electricity costs – the feasibility of am electrification alternative is evaluated with the use of a Levelized Electricity Cost (LEC) aggregating investments and running costs. For each supply alternative (including extending the regular interconnected network) and for each location in a map, such costs are calculated and maps of cost per technology are produced
- Mapping winning technologies – from the mapping of costs for each technology, one may build maps identifying which solution is the most economic to achieve electricity supply in each cell of the map, therefore delimiting regions of interest for each alternative. For instance, one may locate regions of interest for photovoltaics, or isolated wind generators (for water pumping, for instance), or then regions where the best plan is to progressively extend the interconnected network.

Figure 3 shows a map produced for a large region in Brazil, with a final result obtained in the MEAPA project. It matches regions to the most economical technology for local supply, showing the best alternative in each point of the map.

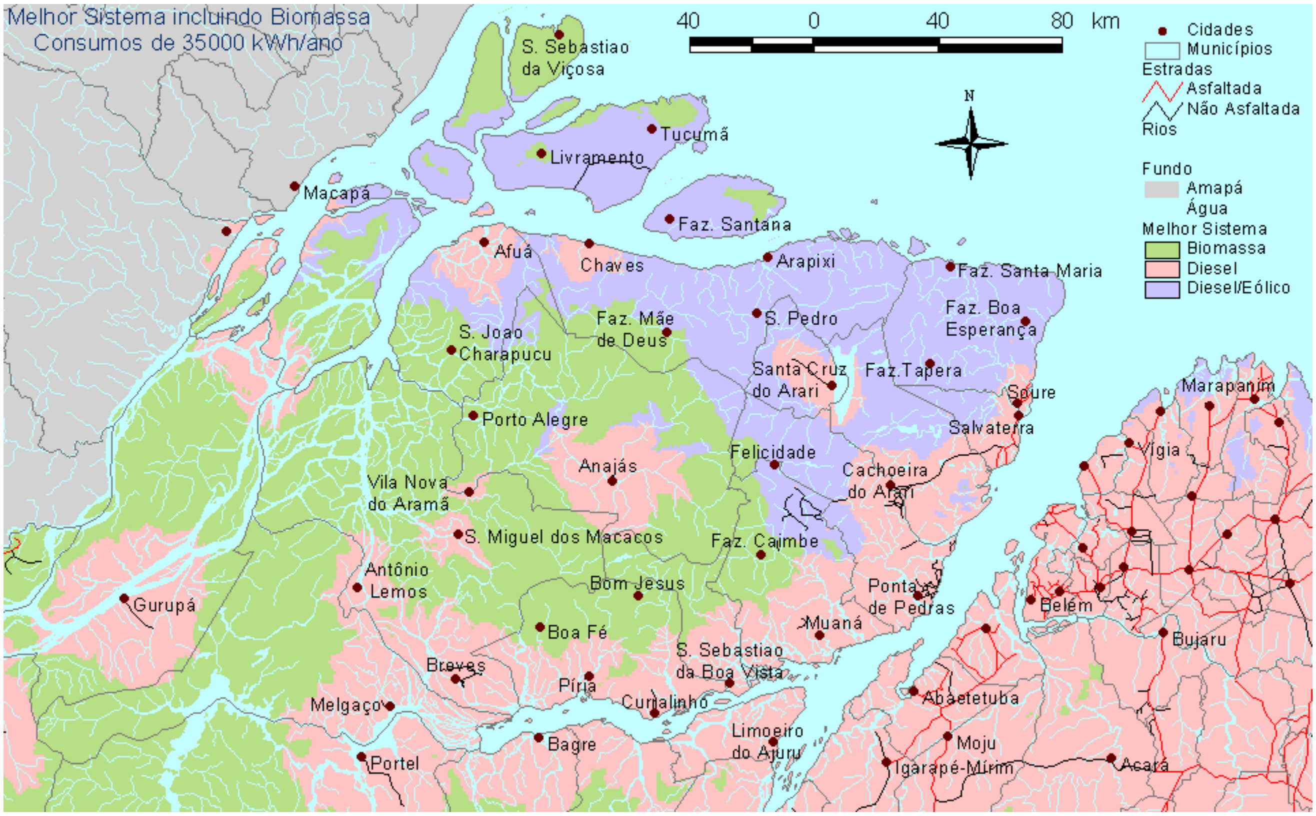

Figure 3 – Map with the winning solutions, comparing diesel generation with hybrid wind-diesel and with biomass, on the basis of their LEC costs, for the electrification of the island of Marajó (Brasil, circa 300 km long, at the mouth of river Amazonas), for local consumptions estimated on the basis of 35000 kWh/year

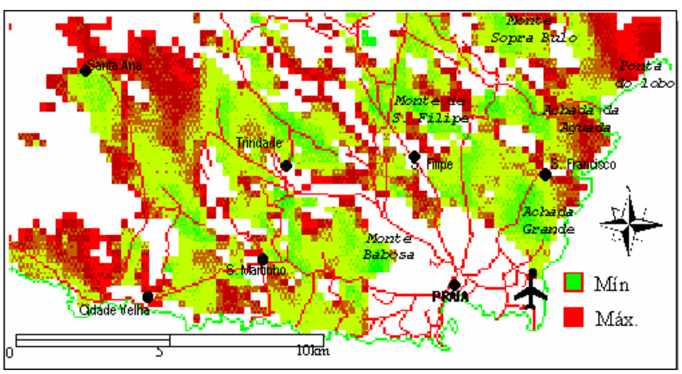

Figure 4 – Map showing economic feasibility to build a wind park in the region around Praia, the capital of Cape Verde (Africa), based on the LEC cost to generate electricity and inject it in the grid, taking in account not only wind availability but also all other costs involved. Colors display different costs and allow the identification of the most profitable locations.

Also, other types of maps may be produced, such as the one in Figure 4 – it is a map showing different energy generation costs (LEC) for different places in the map, taking in account not only wind availability but also costs of connection to the grid, costs of the equipment, costs of maintenance, costs of roads to transport equipment to their place.

These form maps of economic feasibility of wind generation, and not only maps of wind availability (so called wind atlas). They may give valuable indications to investors, as well as to governmental agencies, on the potential of a region or a country.

IV. A Negotiation Aid System to Promote Investment in Wind Generation

One source of constraints to the widespread use of wind generation derives from supra-national, national or local regulations, creating protected zones, natural or national parks, areas of protected bio-diversity or ecologically protected, besides zones close to buildings, airports, etc. or related with the military or possibility of radar confusion.

Another source of constraints derives from the opposition of environmental organizations, who locally object to renewables while at national level continue to claim for their use. Therefore, Government Energy Agencies need to have at hand a comprehensive methodology to try to conciliate the interests of different agents (investors, environmentalists, state agents) in order to organize regional plans for the development of distributed renewable generation [4][5].

An Actor, such as investor or an environmentalist activist, has his own criteria to assess the tolerance (acceptance or rejection) of solutions (to build wind a wind generation facility in a certain location of the territory). Each criterion may have degrees and there is furthermore a concept of relative importance of criteria. An Actor must consider at the same time several criteria "weighted" by their relative attractiveness, and therefore we have modeled the decision process as rules such as

IF a solution is
Far from urban centers *(very important)* **AND**
Close to existing power lines *(important)* **AND**
Has high wind availability *(extremely important)*
THEN the solution is accepted (tolerance index = 1)

This could be interpreted as a form of a Takagi-Sugeno Fuzzy Inference System, as represented in Figure 5.

These rules may be built by two processes of interaction with an Actor: by helping him in defining the importance of criteria, or by getting from him examples of decisions that may serve to train the TS-FIS system, which learns the structure of preferences of the Actor and is then able to reproduce, for the entire map, such decision process, generating tolerance maps, describing the degree of acceptance or rejection of a certain option in each map cell or location. Tolerance maps for distinct Actors are them worked out together in order to discover the areas of least conflict among investors and environmentalist groups.

The following figures illustrate some of the results obtained for La Rioja, Spain. The system was developed with ArcInfo and ArcView tools and is one of the modules of a much more complex set of applications.

The database of the GIS has been filled up with data from La Rioja and modules defining the economic efficiency of renewable energies have been developed; these modules may be used to help defining some of the data necessary to be considered by the Negotiation Aid System.

The simulations represent a Negotiation process between a Group of Investors in Wind Parks and an Environmentally Oriented Group.

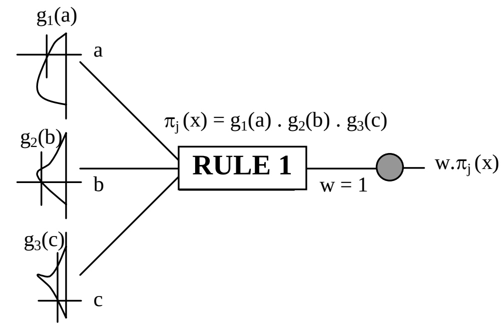

Figure 5 – TS FIS with a single rule: a cell x in a map with three values (a,b,c) in three criteria, giving as output a tolerance index for x.

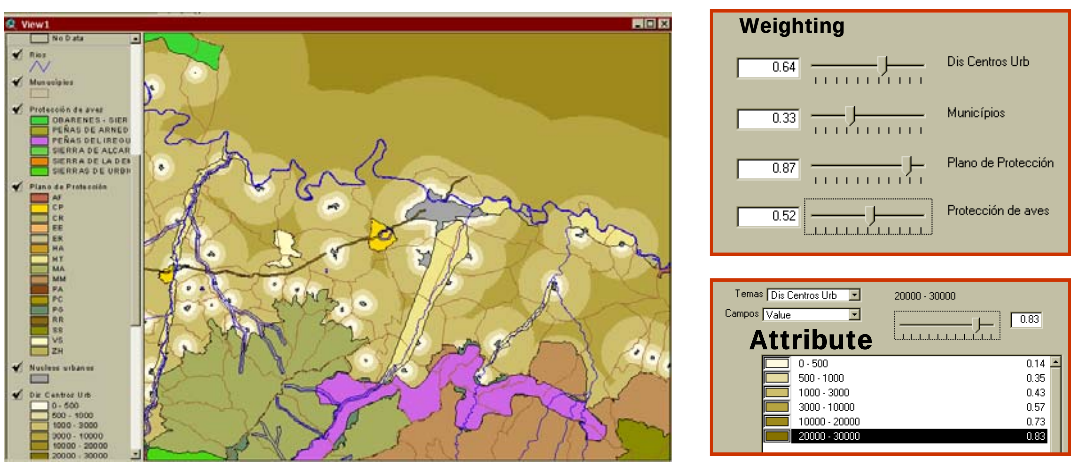

Figure 4 – City of Logroño and surrounding area: map identifying coverages related with distinct criteria and interface allowing an Actor to define his preferences and weights in several criteria (the criteria in the figure are: distance to urban centers, municipalities, nature protection plan, bird protection – output from the actual application).

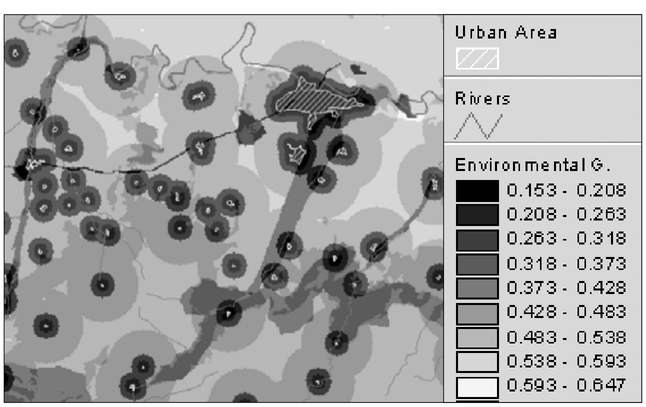

Figure 5 – Tolerance maps for the environment interest group. Dark zones represent sites with lower tolerance. We can observe less tolerable zones near urban centers and in environmental protected areas.

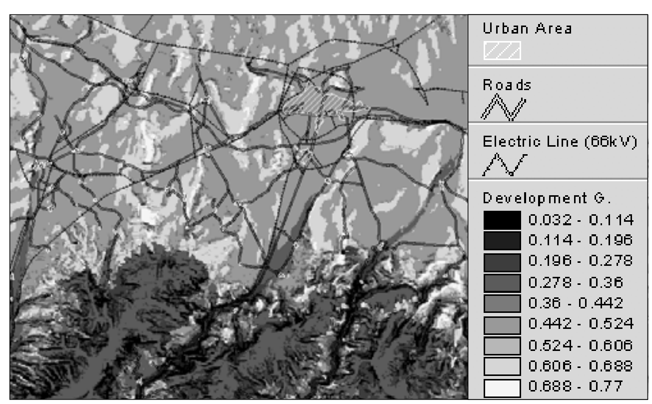

Figure 6 – Tolerance maps for the investor interest group. Dark zones represent sites with lower tolerance. We can observe preferred areas in locations with high potential resources and technically acceptable sites.

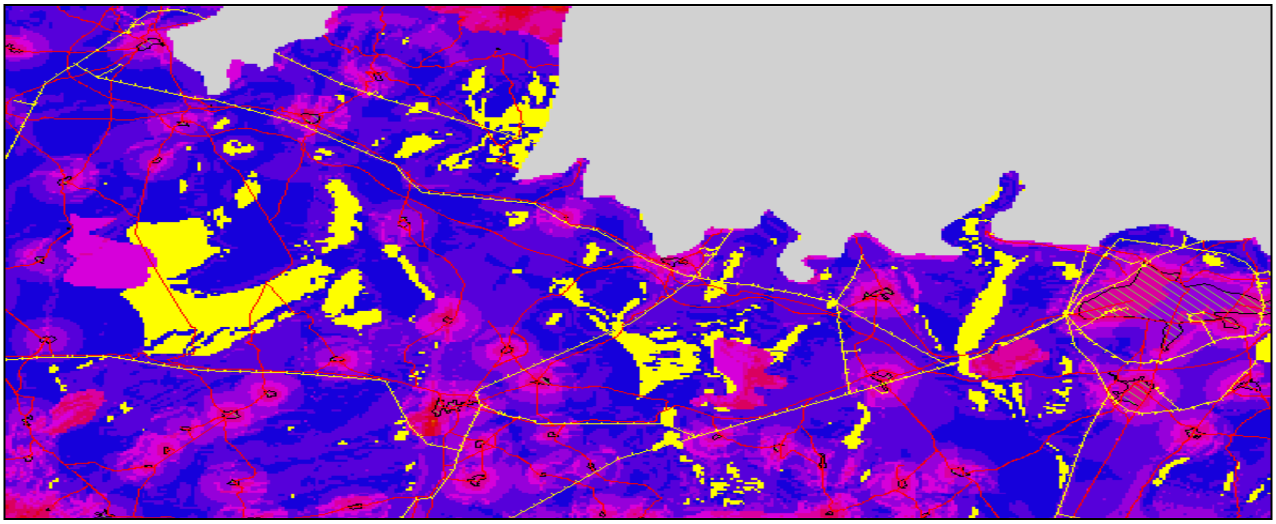

Figure 7 – Region in La Rioja. Simulation of a conciliation process between two Actors, representing a Group of Investors and an Environmentally Concerned Group: identification of areas of coincidence of choice and areas of no agreement, for the development of wind parks of 220 MW.

V. Wind Power Prediction

Wind power prediction is now an active research topic, because of its economic and security importance. In fact, in a market environment, wrong predictions about wind power may lead to the distortion of market prices. Also, a high penetration of wind power may lead to both dynamic security problems and to availability difficulties, when facing a global wind speed drop.

Wind forecasting is a step in this direction and several models are being developed and tested. But ir is not enough. From general wind forecasting, one must generate power injection predictions for a diversity of wind parks. The power output from a wind park depends on a number of factors, namely the direction of the wind and the local topology of the terrain.

We present now an example from a real case. The data have been gathered in a region of northern Portugal; they are composed of three time series: wind speed, wind direction and power output of a wind park, collected every ten minutes. We dealt with data collected from January 1, 2004 to February 20, 2005. For confidentiality reasons, actual power output has been transformed into a percentage of maximum available capacity of the park, which has a considerable number of generators of close to 1 MW each, spread over mountain tops, in a total installed capacity of about 40 MW.

In Figure 6 we present a plot of untreated data, as collected from the SCADA system, showing 9993 measurements of wind speed vs. wind park power output. This set presents odd values and had to be cleaned up – for instance, you will notice points with high wind speed and no power output, due to park disconnections.

In Figure 3 we plot the same data showing wind speed and direction, as measured at a point close to the wind park.

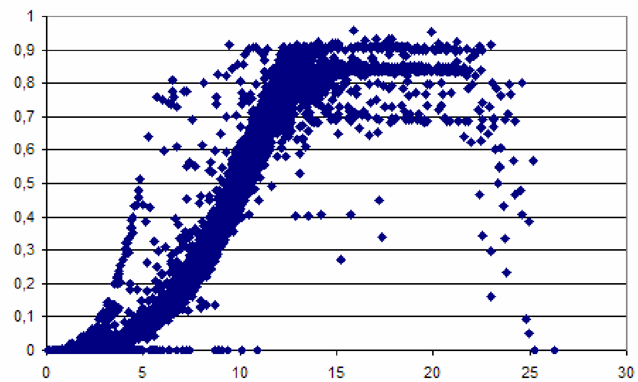

Figure 6 – Plot of wind speed (x axis) vs. power output of the wind park (y axis). Power output is represented in p.u. relative to the total installed capacity. Data untreated.

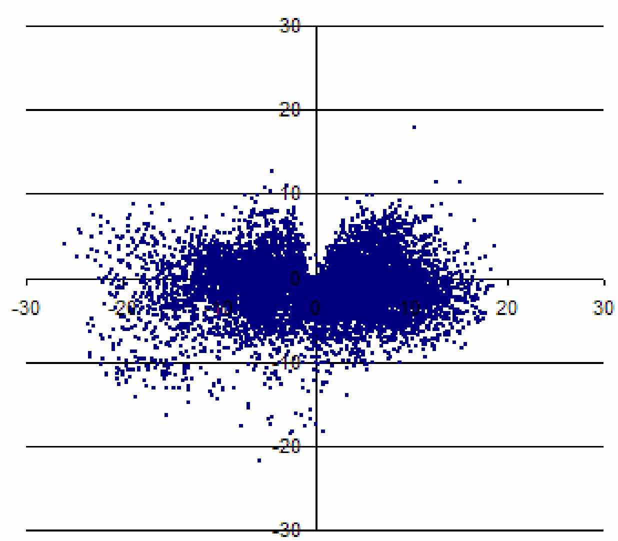

Figure 7 – Distribution of wind speed (in m/s) and direction at the measuring point near the wind park

To predict power generation form wind prediction, we have used a 0-order Takagi-Sugeno fuzzy inference system (TS-FIS). In a TS FIS, one has rules that are fuzzy in their antecedent and crisp in their consequent. A general form of a rule k with output y_k is

IF (x_1 is A and … and x_p is Z) THEN $y_k = y(\mathbf{x}, \mathbf{w})$

The antecedent of rule k is a fuzzy set whose membership function g_k is the intersection of fuzzy sets describing conditions A,…,Z. Usually, the T-norm used to represent intersection is the product (of the membership values of each input variable).

The consequent of a rule k is a function f_k of inputs. In 0-order TS-FIS, f_k is constant and, therefore, $f_k = w_k$.

The output of a TS-FIS is a weighted sum of the responses of all the rules

$$y_i = \frac{\sum_{k=1}^{R} g_k w_k}{\sum_{k=1}^{R} g_k} = \sum_{k=1}^{R} \bar{g}_k w_k \quad , \quad \text{with } \bar{g}_k = \frac{g_k}{\sum_{k=1}^{R} g_k}$$

These concepts are illustrated in Figure 8.

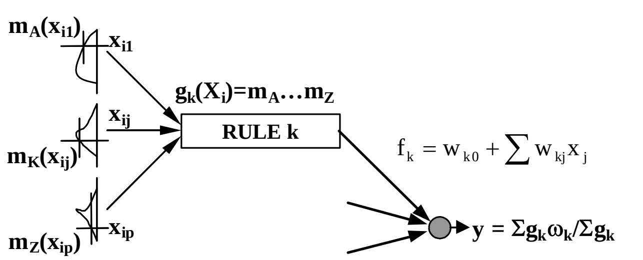

Figure 8 – TS-FIS scheme. Each input pattern X activates some membership functions; the combination of these fires a rule k with strength g_k. The weighted combination of rule firing strengths gives the output of the system.

We have selected 5000 points from the data available, to train and test the FIS, and divided them in a training set of 1000 points and a test set with the rest of the points.

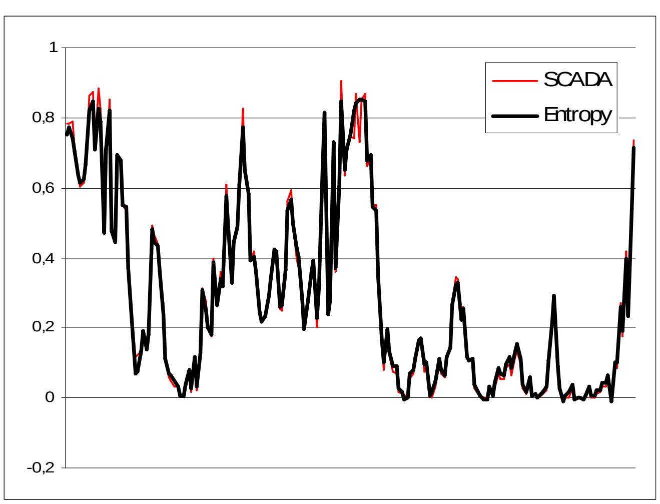

Figure 9 – Comparison between actual power measurements at the SCADA system of the wind park and the prediction made by a Takagi-Sugeno FIS, trained by an evolutionary particle swarm algorithm to minimize the entropy of the prediction error distribution.

In Figure 9 we see, in a subset of the test set, a comparison between the prediction and the actual value recorded by the SCADA system of the wind park. This was achieved by a training procedure using an EPSO algorithm (Evolutionary Particle Swarm Optimization) to optimize the weights of the FIS, relative to a criterion of minimum entropy of the distribution of errors. The accuracy of the prediction is good.

Tools such as these will eventually become a basic component of control applications in modern power systems.

VI. EMS for Isolated Systems with High Wind Penetration

The importance of developing new tools for the operation of isolated systems with high penetration of renewables, namely wind, has been recognized in the European Union and as early as 1994 projects were developed in the JOULE programme to deal with this new problem. This resulted in the development of new EMS concepts and software applications, that were first applied to the island of Lemnos (Greece) [6] and later to Crete (Greece) and now are being installed in the islands of Azores and Madeira (Portugal). The latest format is a result of the project called MORECARE [7] and deals with the unit commitment and generation dispatch of conventional generation, together with renewables (hydro, wind and solar photovoltaic).

Among the innovative features of the MORECARE EMS, one may indicate modules not only for load forecast but also for wind forecast; furthermore, also modules to assess in real time the dynamic security of the system have also been built.

The use of computational intelligence tools is widespread. For instance, the unit commitment module searches for generator schedules with a Genetic Algorithm; the preventive security assessment module uses both a neural network and decision tree concepts.

Figure 10 displays the main characteristics of the power system in Crete. Some of the wind parks are installed at an extremity of the island, with a single link to the main 150 kV loop, a situation that increases concerns about security. Occasional blackouts were not unheard of, in the past.

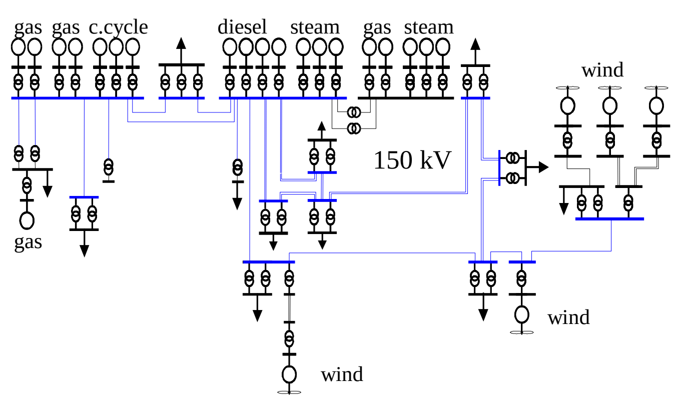

Figure 10 – Power system in Crete, Greece, with a mix of generation technologies including wind generation, with 550 MW of installed capacity (including 80 MW of wind generators) and a peak load of 350 MW.

The unit commitment module relies on a Genetic Algorithm that produces a first schedule for the next 48 hours, and then updates this schedule every 20 minutes for the next 8 hours. The model takes in account all costs, including fuel costs and start up and shut down costs, and constraints such as related to ramping and rules for taking load, minimum shut down times, spinning reserve criteria and wind penetration criteria. Figure 11 illustrates one result form running the 48-hour GE-based unit commitment module, depicting the schedule for all generators as well as the participation of wind generation.

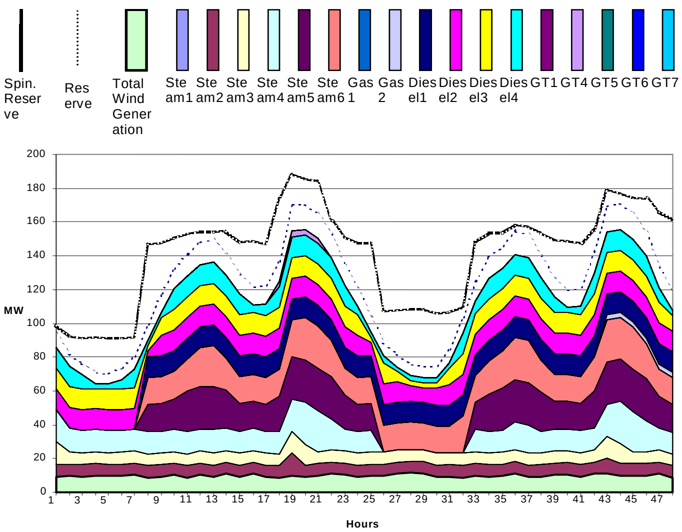

Figure 11 – Solution for a long-term UC. The base strip corresponds to wind generation. The spinning reserve criterion is satisfied (and other constraints).

To assess the security of an operation point, relative to contingencies, one may use a neural network especially trained to recognize frequency excursions as a result from a given set of contingencies. Frequency deviations must be limited to a certain threshold; otherwise relays will trip causing a possible blackout in the island.

An initial set of 60 input variables describing an operation point has been reduced to only 6 significant variables by applying a technique of feature selection [£]: the active load at bus 1, the active power from generator 1 and the spinning reserve of machines 2 and 5; the other variables are related with the characterization of the active and reactive load and wind generation profiles.

A feed-forward neural network adequately trained achieved a performance of 99.8% of correct classification of operating states in the event of contingencies, identifying that a frequency deviation below 49 Hz would be expected. The same quality of results was attained for other frequency thresholds. This means that, given an operation point proposed by the dispatch routine or observed by the operators, an almost instantaneous assessment of its security is produced on-line in the EMS, allowing operators to apply preventive measures. Without these techniques from computational intelligence, it would have been virtually impossible to obtain such result.

VII. Loss reduction and Voltage/Var control, taking advantage of distributed generation

The appearance of private dispersed generation, linked directly to the distribution networks, at voltage levels such as 60 kV and 15 kV, has been seen as a source of problems by distribution utilities. In fact, because these generators (mini-hydros, diesel or natural gas, wind parks, biomass, co-generation/chp) are not under the control of the company, network flows become much more unpredictable; and because they usually result from private initiative, planning the network must take in account extreme scenarios such as having a high amount of generation branched (and where?) or not having at all.

Rules in most countries, namely because of the fear of problems with reactive power flows, especially in the presence of induction machines, are strict in specifying mandatory measures such as the installation of an important value in capacitor compensation or fixing a high reactive power factor at the points of injection.

However, another possibility is open at distribution level, which opens a new form of business: passing the control of reactive power from the private owners to the grid operator. This has been investigated in an European Union country by building a sort of OPF (optimal power flow) for distribution systems to assess the possible benefits for the grid of an adequate manipulation of controls at distributed generation sites, in terms of loss reduction and improved voltage profiles.

For confidentiality reasons, we can only give some general information about the system. The studies concern a region in Europe with a distribution system composed of a high voltage 60 kV meshed network and of 30 and 15 kV Medium Voltage open-loop networks. Two load scenarios were defined: peak and off peak.

In the 60 kV level we have

Buses	Lines	Generators	Transformers	Capacitors	Loads
50	37	36	26	10	16

At 32 buses we have control availability, through action on generator excitation or on systems with controllable electronic interface (16 cases), on capacitor banks (12 cases) or on transformers with tap changers. In 6 buses we find also generation with induction machines directly branched. The distributed generation profile is as follows:

Generators	Type	No.	Installed capacity (MVA)
hydro	Synchronous	17	105.6
	Induction	2	1.0
wind	Synchronous	5	34.6
	Induction	8	46.6
Total		32	187.8

The installed capacity in distributed generation amounts to 85% of the peak consumption (aprox. 220 MVA). This may cause power to flow upward to the 220 kV transmission system, which is not convenient namely for legal and contractual reasons.

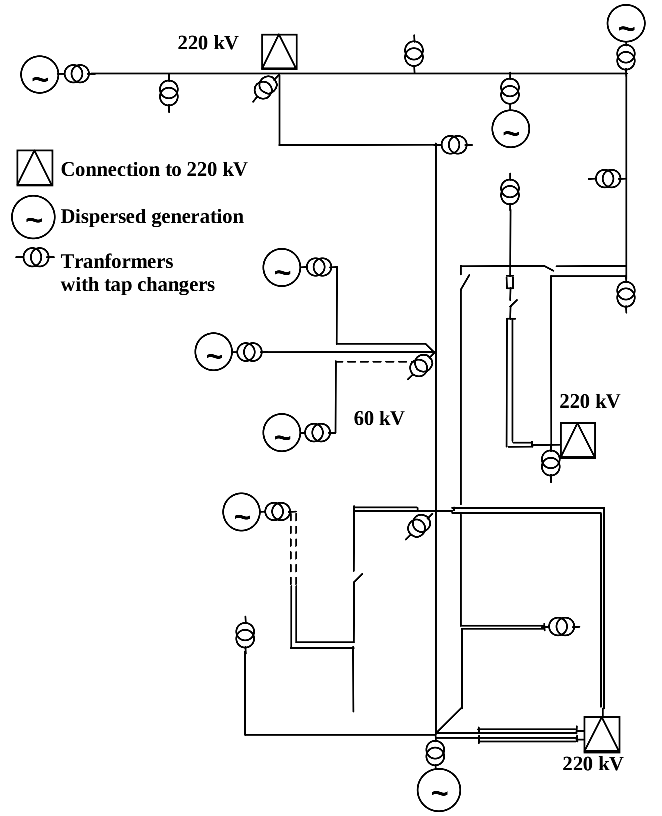

Figure 12 – Simplified scheme of the 60 kV network, with three connection points to the 220 kV transmission system. The distributed generation is composed of hydro and wind generation and owned by private investors.

A number of scenarios were defined, based on the historical behavior of the independent producers. In the off-peak period, for instance, the hydro generation was set to 30% of the installed capacity while the wind generation was set to 60%. The off-peak period has a load of 40% of the peak hour value. Figure 12 presents a diagram of the 60 kV system.

A 15 kV system was also studied, with the following dimension:

Buses	Line s	Generator s	Transformers	Capacitor s	Loads
361	364	11	2	1	178

In this system, 11 independent private small generators are branched, all acting in an industrial co-generation process (CHP – combines heat and power), with synchronous generators ranging from 4.645 MVA to 8.2 MVA, in a total of almost 65 MVA.

The objective has been set as the minimization of power losses for both load periods. The optimizations have been successfully reached with an EPSO model with discrete and continuous variables, in a platform developed at INESC Porto. EPSO is an Evolutionary Particle Swarm Optimization method which has been demonstrationg to be very reliable [8].

Some of the interesting results achieved were:

a) on the 60 kV system a reduction of 16% in power losses would be possible, while improving voltage profiles and keeping all variables within operational limits;

b) general raise in voltage values at the 60 kV level and correction of some excessive over-voltages

c) further reductions in losses achieved on the 15 kV systems

d) strong correction of the tan ϕ values at the distributed generation buses, by abandoning the previous rigid operation conditions (legally imposed) and negotiating the passage of control to the utility; in fact, many distributed generators become free from supplying reactive power, contrary to the most usual legal conditions imposed

e) de-congestion of system lines; in one case, power flow would reduce almost three times.

The practical important conclusion is that the presence of distributed generation may be transformed in a useful tool for distribution companies with interesting gains in loss reduction and improvement of voltage profiles.

This has an implication: that the regulatory frameworks allow space for negotiation between distribution companies and private distributed generation so that reactive power may be globally controlled. It also means that simplistic legal mechanisms, such as fixing some tan ϕ or cos ϕ at the connection point of a small generator, may in fact do more harm than good to the global interest of companies, independent generators and customers (who will, in the end, pay for the inefficiency of the system).

VIII. Expansion Planning in Systems with High Penetration of Volatile Renewables

The European Union policies have led to a remarkable increase in wind generation, which will grow in the coming years due to the commitment to the Kyoto agreements. However, the volatility of renewables, namely wind generation, adds concern to planners about the safety of the systems. Probabilistic methods have been regularly accepted in generation planning but transmission system planning is widely organized respecting a N-1 criterion. The conciliation of these two approaches has been achieved by a method called *Well Being Analysis*, proposed by Roy Billinton [9]. We may report here its application to the Portuguese transmission system and to its evolution from 2002 to 2010.

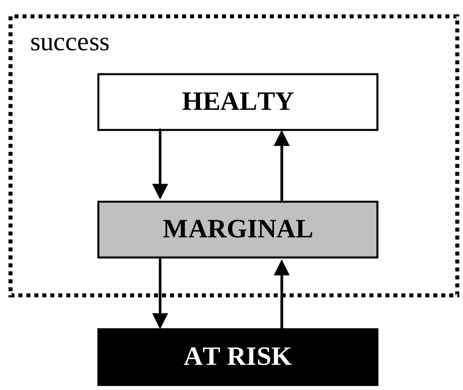

Figure 13 – State classification in Well Being Analysis

In Well Being Analysis, system states are classified as healthy, if the N-1 criterion (or other deterministic criterion) is satisfied, marginal, if the N-1 criterion is no longer satisfied but the operation is still possible, and at risk, if load curtailment becomes necessary (see Figure 13).

The Portuguese system configuration for the year 2002 had 479 units with a total installed capacity of 10.90 GW, distributed as follows: 4.15 GW (Hydro); 4.86 GW (Thermal); 0.17 GW (Wind); 0.30 GW (Mini-hydro); and 1.42 GW (Co-generation). The annual peak load occurred in December and it was approximately 7.40 GW. The static system reserve corresponded to 32% of the installed capacity. Also, the amount of renewable power in the system is 42% of the total capacity.

In the 2010 scenario, the system will have 1668 units with a total installed capacity of 17.83 GW, distributed as follows: 4.94 GW (Hydro); 6.27 GW (Thermal); 3.75 GW (Wind); 0.45 GW (Mini-hydro); and 2.42 GW (Co-generation). The expected annual peak load forecasted for 2010 is 10.59 GW. The static reserve is now 40.6% of the total installed capacity. Actually, we now know that installed wind generation in 2010 is likely to reach 5 GW – so, the studied scenario is still conservative.

A chronological Monte Carlo model was developed to estimate reliability and security indices of the system in both scenarios. This included models for hydro and thermal units, wind generators and wind series, mini-hydros, private co-generation (chp), maintenance effects and load behavior. Also, four studies were defined: BC – base case, using historical hydrological and wind series; HW – simulating the most severe historically observed conditions in terms of rain and wind (little rain and wind); HWM – same as HW but with an increase in 20% of generating capacity in maintenance; HWz – the same as HW but with no wind.

Results may be found in [10]. Some of the most interesting conclusions are:

- The base case BC presents no problem; the Loss of Load Expectation (LOLE) presents only a slight increase from 0.19 to 0.26 h/year; the expected residence time of the system in marginal states (E_M) increases from 1.92 to 2.37 h/year, with a frequency (F_M) raising from 1.4 to 1.9 occurrences/year.
- The HW case shows some degradation of the indices but still not at serious levels.
- The HWM case has indices well within acceptable thresholds in 2002 (like LOLE of 2.59 y/year) but presents unsatisfactory values in 2010 (LOLE of 11.01 h/year, above an internationally accepted limit of 10 h/year); the expected time in marginal states E_M would be 52.42 h/year, with a frequency F_M of 37.06 occ/year. We clearly see the effect of maintenance in these indices.
- The HWz case is still acceptable in 2002, with LOLE of 0.72 h/year, E_M of 6.45 h/year and F_M of 4.48occ/year. However, in 2010 LOLE would raise to 34.78 h/year, a totally unacceptable value. Moreover, E_M would be of 124 h/year and F_M would reach 84.16 occ/year.

Notice this result from the well being analysis: 84 times per year, the system would be expected to operate in alarm condition! There is no visible failure to the consumers, however the operating conditions would be pretty stressed, at a cost not difficult to evaluate that would be substantially higher than in normal condition.

Other results from the Monte Carlo analysis confirm the following: the addition of a large fraction of wind generation to a system may not increase noticeably the loss of load expectation, but will increase highly its variance. This means that the *risk* of having a major failure increases, although the average value is still the same. This underlines the importance of evaluating variance, especially in the presence of a high penetration of renewables.

Also, the Well Being Analysis approach allows us to understand that the operation of a system should not be judged only in terms of the classical average indices for failure. It is also important to evaluate the conditions of "normal" operation and verify the emergence of marginal states, where security conditions are no longer observed.

IX. Conclusions

Renewable energies and especially wind generation have passed from a state of marginal or alternative source to an important mainstream solution, as respectable as any other. However, because of wind characteristics, a number of new problems arise which were not really relevant in the past, and for which both companies were not prepared and software applications were not ready to cope with.

This paper did not try to list all problems or to index all solutions. However, it tries to highlight that to these problems new methods of solution have also emerged in the scientific community. To make this case, a number of examples have been briefly referred to, from forecasting to security control, from negotiation to wind park location, from energy resource evaluation to unit commitment, from reactive power control to reliability assessment.

In all these cases, we witnessed an abundant use of computational intelligence tools, namely evolutionary algorithms, fuzzy inference systems and neural networks together with chronological Monte Carlo simulation. We also noticed the growing importance of integrating these tools in a GIS environment, especially at distribution level.

Utility engineers and decision makers must become aware of the new problems, but also of the new solutions at hand.

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XI. Biography

Vladimiro Miranda received his graduation, Ph.D. and Agregado degrees from the Faculty of Engineering of the University of Porto, Portugal (FEUP) in 1977, 1982 and 1991, all in Electrical Engineering.

In 1981 he joined FEUP and currently holds the position of Full Professor (Professor Catedrático). He has been also Full Professor in the University of Macau (China).

He is also currently Director of INESC Porto (Institute of Engineering in Systems and Computers), a private non-profit research institute in information technologies, communications, power systems, manufacturing systems engineering and optoelectronics and optics.

He has authored many papers and been responsible for many projects in areas related with the application of Computational Intelligence to Power Systems.