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A new approach for power system online DSA using distributed processing and fuzzy logic

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Abstract

In this paper, a new approach for power system online dynamic security assessment, as well as a tool for calculating the proposed fuzzy dynamic security index is presented. This proposal is based on a three-stage fuzzy inference system, which composes the fuzzy dynamic security index making use of seven performance indexes herein defined. The calculation of the performance indexes is based on the results obtained through dynamic simulations of the system behaviour after each one of the credible contingencies in a given operation state. With the aim of reducing the calculation time a novel distributed processing of the dynamic simulations is also developed. High voltage systems are used to illustrate the ideas presented in the paper.

Keywords: Dynamic security assessment; Full simulations; Fuzzy dynamic security index; Fuzzy inference system; Distributed processing

1. Introduction

Secure operation is one of the most important requirements of power systems. However, due to the competitive conditions of the present-day electrical markets, the security level in which these systems operate has been reduced due to the tendency to make maximum use of the generation and transmission systems. In order to take the control actions necessary to improve security it is essential to assess both the static and the dynamic security level. The static security assessment (SSA) is made by comparing the steady state system variables with their admissible limits. Reduced calculation times allow the implementation of an online SSA analysis. The dynamic security assessment (DSA), in turn, analyzes the transient dynamics developed in the period following a contingency [1,2]. In this way, the stability of the system in each analyzed contingency may be determined. Due to both, the large size of power systems and the large number of components, longer calculation times are required. The time needed for obtaining the results is longer than that available for taking the above-mentioned control actions, in case these are necessary.

The dynamic security assessment may be made by using either approximate methods or full simulations (time-domain numerical integration) [3]. The approximate methods include techniques such as sensitivity methods for assessing the voltage security and direct methods for assessing the transient stability such as Lyapunov-like methods, methods based on the equal-area criterion, etc. Whereas full simulation methods include power flow solutions of PV curves, that is, voltage curves in terms of the active power, used to define the collapse point of the steady-state voltages, time-domain full simulations for transient security and analysis of eigenvalues for assessing the small signal stability. Although approximate methods offer some computational advantages, full simulation methods provide a more precise assessment. Another advantage of full simulation methods is that they make possible both to have knowledge of the post-contingency state of each system variable and to use various models of system components depending on the degree of detail required. When an approximate method is used, some assumptions are made which must be verified in order to confirm the applicability when the system conditions change. This verification is not necessary when full simulation methods are

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used, a fact that is regarded as an additional advantage of these methods [4].

A great disadvantage of the full simulation methods, which is currently rather regarded as a challenge, is the extent of time required for calculation. This difficulty becomes greater when more detailed models are used and also when there is an increase in the size of the power system under analysis. Therefore, in order to exploit the most of the advantages of such indirect methods, the time for the calculation involved must be reduced, both in dynamic simulations and in the analysis of the results. This work presents a DSA methodology, which reduces the calculation time of indirect methods such that it makes possible their use online. This is achieved through the use of both the distributed processing of dynamic simulations and the application of artificial intelligence techniques in the analysis of the results.

The paper is structured as follows: Section 2 briefly describes the methodology for online DSA proposed here. The distributed processing of the dynamic simulations is described in Section 3, and also a brief discussion of the simulation times is included. Section 4 presents the methodology stage for analysis of the results obtained by the dynamic simulations. It includes the definition of the performance indexes and also the description of the fuzzy inference system (FIS) used for the composition of the dynamic security index. In Section 5, the test system model based on the Argentinean power system is described, as well as the results of applying the proposed methodology for DSA are discussed. Finally, Section 6 summarizes the main contributions of this paper.

2. Methodology for power system online DSA

The proposed methodology is summarized on Fig. 1. Beginning from an operating state of the system, dynamic simulations are made in order to determine the system behaviour after each of the various critical contingencies considered. The simulated contingencies are events that are completely independent from each other; therefore, the distributed processing may be used for such a task. These simulations provide detailed time-domain descriptions of the physical phenomena developed in the transient period following the contingency. Finally, based on the dynamic responses obtained from the different system variables, results are analyzed. In this module, three actions are taken. The first one is related to calculating the performance indexes, which take account of the post-contingency behaviour of the system variables (angles, frequency, voltage, etc.). The second one is related to composing indexes through the use of a tool based on fuzzy logic. Finally the third one is related to composing tables and graphs in order to show the security assessment results in a clear and efficient way.

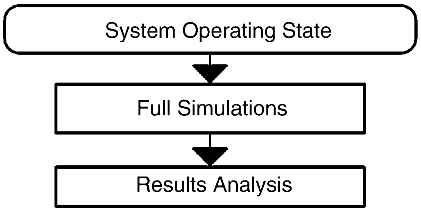


Fig. 1. Methodology for online power systems dynamic security assessment.

In order to determine in an online application the system operating state which dynamic security will be assessed, it is necessary to acquire measuring data from different system variables. This could be made using for example: SCADA systems, Phasor Measurement Units (PMUs), or power system disturbance monitors [5,6]. However, the data acquisition is out of the scope of this work. Here is assumed that the required data are available and the operating state is already determined. In the two next sections are explained in detail the second and third stages of the methodology shown in Fig. 1.

3. Full simulations stage

The dynamic simulation module is aimed at determining the system behaviour after each of the contingencies to be assessed for a given operation state. In what follows are presented some features related to the distributed processing program developed, its operation and the resources it makes use of. Finally, calculation times are presented for the distributed program in two power systems, a relatively simple one and a larger system based on the Argentinean electric power system. These calculation times are compared with the time the simulations would take in case they were sequentially executed.

3.1. *Program features*

The distributed processing program used for the dynamic security assessment is in turn made up of two parts, the client program and the server program.

The client program is in charge of building the input file for the simulation process, which contains both the data from the power system under study and a list of contingencies to be simulated. This program is in charge of starting up the dynamic simulations process, including checking up the available servers in order to verify whether they are active and ready. It is also in charge of sending the input file and the contingency that must be evaluated by each server. Once this process is carried out, there is a delay time until all of the contingencies have been assessed. Finally, the client receives the output data of all of the servers and saves them in an output file for further use.

The server program, in turn, is in charge of executing the simulation process. A number of server programs are run in different PCs; the maximum amount of PCs required equalling the number of contingencies that must be assessed. However, there exists the possibility that a server may assess more than one contingency; the number of PCs required being consequently reduced. The various servers are in charge of receiving the input file and executing the dynamic simulator program SiCoDiS, which is in charge of evaluating the system behaviour during the contingency considered. The structure of the distributed processing with the client program and the various server programs are shown in Fig. 2.

SiCoDiS has appropriate models of the power system components, including the generating units, the network and the loads. It also includes appropriate models for load shedding due

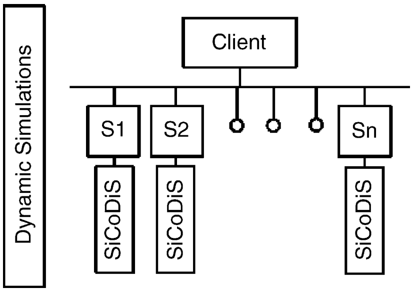


Fig. 2. Distributed processing of power system dynamic simulation.

to under-frequency and rate of change of frequency. The component models form a set of algebraic–differential equations. The system thus modelled is affected by the contingency and SiCoDiS carries out the dynamic simulation through a recurrent process of integration of the differential equations (fourth-order Runge-Kutta method) and of power flow calculation (Gaussian elimination method). In order to calculate the power flows in the initial operating state prior to the fault, the Newton-Raphson method is applied.

3.2. Resources used—operation

The distributed processing is implemented in PCs that are arranged in a LAN network. The client program runs in one of these PCs whereas the server program runs in several additional ones as required according to the number of contingencies to be evaluated. The LAN network is of star-type (see Fig. 3). The use of these PCs has the advantage of low cost distributed processing.

Both the client and server programs are written in Java language. Prominent features of this language are: it makes possible the independence from the operating system as well as from the manufacturer; it is reliable, secure, robust and flexible. In other words, it is open to changes and updating, which improve above all the operation of the distributed processing program.

In addition to the above mentioned advantages, the main feature of the Java language is that it has a useful tool for developing distributed applications, the remote methods invocation (RMI). RMI allows a PC-executed program to call methods (functions) from other programs executed in other PCs. In addition, RMI provides the mechanisms necessary for several distributed programs to communicate and transmit information to each other [7].

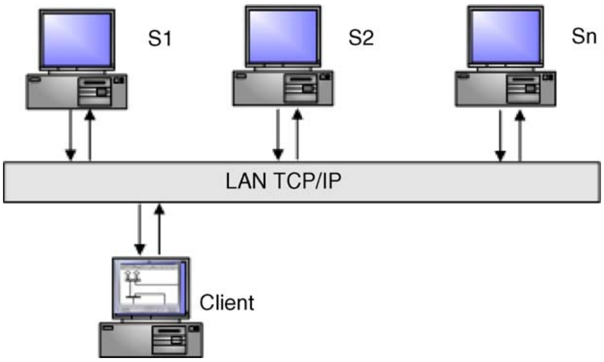


Fig. 3. Lan network.

Table 1
Features of the PCs

Number	Characteristics		Operating systems
	Type	RAM	
1	AMD 1,325 GHz	512 MB	Win2000
2	Pentium II 300 MHz	256 MB	Win2000
3	Pentium II 350 MHz	768 MB	WinXP
4	Athlon XP 2.0 GHz	1 GB	WinXP
5	Athlon XP 2.1 GHz	512 MB	WinXP
6	Athlon XP 2.1 GHz	512 MB	WinXP

3.3. Calculation time

In order to show the merits of the distributed processing two power systems models are used, a 21-node one and another, obtained from reducing the Argentine electric power system to obtain an equivalent system of 65 nodes. For obtaining the calculation times six PCs are used. The features of these PCs, type of processor and RAM memory, and the operating system installed in each of them are shown in Table 1. Both the client and the server programs have been totally developed at JBuilder 2005 [8], by making use of the Java SUN Virtual Machine JDK 1.5.0 [9].

3.4. 21-Node system

Table 2 shows the calculation times involved in the 21-node system. In this system, 24 contingencies were assessed (12 generators outages and 12 transmission lines outages), plus the base case. T1 stands for the sum of the time taken by the client to verify whether the servers are ready and the time required for preparing the various running threads (one for each contingency to be assessed). T2 is the time taken by the distributed processing, that is the servers, in simulating all of the contingencies and returning the simulation results to the client. The first row of the table corresponds to the sequential calculation time.

3.5. Argentinean system

Table 3 shows the calculation times involved in the Argentinean system. In this system, 61 contingencies were assessed (15 generators outages and 46 transmission lines outages) plus

Table 2
Calculation time for the 21-nodes system

PC number	Numbers of PCs	T1 (s)	T2 (s)	T total (s)
1	1	4	35	39
2	1-2	4	30	34
3	1-2-3	5	22	27
4	1-2-3-4	5	20	25
5	1-2-3-4-5	5	15	20
6	1-2-3-4-5-6	5	8	13

Table 3
Calculation time for the Argentinean system

PC number	Numbers of PCs	T1 (s)	T2 (s)	T total (s)
1	1	38	303	341
2	1-2	37	240	277
3	1-2-3	38	220	258
4	1-2-3-4	39	129	168
5	1-2-3-4-5	40	87	127
6	1-2-3-4-5-6	40	60	100

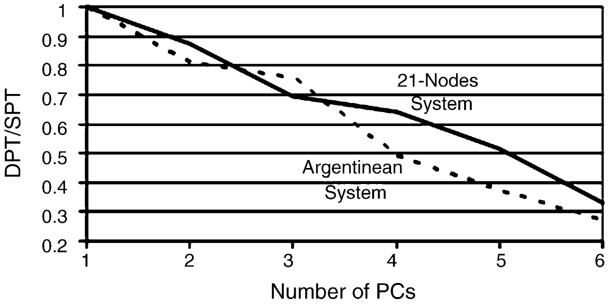


Fig. 4. Simulation time vs. number of PCs.

the base case. T1 and T2 stand for the times previously mentioned.

3.6. Calculation time analysis

As shown in Table 2 and in Table 3 the PC used as client has also been simultaneously used as server, thus allowing simulating some contingencies during the simulation delay times of the other servers. The simulation process consists in moving one running thread (one contingency) in each server PC; the client program detects when one of the contingencies simulation finishes and immediately sends another thread and so on until all of the threads are executed.

Fig. 4 shows the distributed processing time (DPT) relative to the sequential processing time (SPT) using different number of PCs for both simulated systems.

Due to the larger size of the Argentinean system, the process of simulating each individual contingency (time T2) takes longer than in the case of the 21-node system. Likewise, time T1 is longer in the Argentinean system case (65 nodes system). Table 4 shows the average simulation times of one contingency for each system considered.

Therefore, the larger the size of the system the higher the number of contingencies to be assessed and the longer the simulation time of each of them takes. As a consequence, the use of distributed processing turns out to be not only necessary but essential.

Table 4
Simulation of one contingency

T1 (s)	T2 (s)	T total (s)
21 Nodes		
0.19	1	1.19
65 Nodes		
0.6	5.41	6.01

4. Results analysis stage

The module for the results analysis carries out three important tasks: the calculation of the seven partial performance indexes taking into account the post-disturbance behaviour of the system, the composing of five indexes through the use of an artificial intelligence technique (fuzzy logic) for obtaining the fuzzy dynamic security index, and the building of tables and graphs in order to show the results of the dynamic security assessment in a clear and simple way.

4.1. Calculation of the performance indexes

From a dynamic point of view, a power system is secure if, it will “survive” the ensuing transient following to a disturbance and it will move to a new steady state condition. The most important fact is that the transition from the initial state to the post-disturbance final state does not cause other outages that can lead the system to a complete blackout. The criterion to define the performance indexes is based on two important aspects related to the post-disturbance transition:

- an unacceptable performance is related to large variations of system variables, particularly voltages and frequency;
- the ensuing post-disturbance system trajectory will converge to an acceptable steady state condition.

According to the analyzed bibliography, in order to carry out a complete dynamic security assessment, the contingency types to be evaluated are the following: generators outages, transmission lines outages and three-phase faults of lines near the generating machines.

Nevertheless, nowadays, the synchronous stability problem has been fairly well solved by fast fault clearing, thyristor exciters, power system stabilizers, and a variety of other stability controls. Fault clearing of severe short circuits can be less than three cycles (60 ms for 50 Hz frequency). With such short clearing times, and considering that most EHV faults are single-phase, the removed transmission lines may be the major contributor to generator acceleration [10]. In this work unexpected generators outages and transmission lines outages are regarded as possible contingencies for assessing dynamic security.

The occurrence of an unforeseen disturbance like a generator outage or transmission line outage causes a subsequent unbalance between power generation and load. This unbalance is first compensated through the kinetic energy of the rotating masses of generating units and motor loads, leading to a frequency drop. Then the generators power outputs are increased due to the governors’ action (primary reserve). Moreover, when the frequency drops at certain pre-fixed values the under-frequency load shedding is activated. This mechanism helps to bring the system to a new stationary state. The new state of equilibrium is reached within approximately 20 s after the contingency. This time period depends on the size of the system, the magnitude of the disturbance, the types of governors, the availability of spinning reserve, and the amount of load that can be disconnected. In order to include the dynamics of such mechanisms that help to recover the system operation, it is necessary to assess the performance of the system 20 s following the disturbance [1]. This is the time-frame considered in this work.

The mentioned unbalance between power generation and load provoked by the unexpected outages of generators or transmission lines modifies the normal operation values of the power system variables, such as machines angles, frequency and voltage. In some cases this may even lead to a change of these variables out of their range of admissible values. Also, the power flows through the transmission lines are affected by the contingency. In the most severe cases, this would cause the loss of transmission lines due to protective relay tripping. Another effect is the possible loss of load due to the operation of the automatic scheme of load shedding. To quantify the magnitude or degree in which the mentioned variables of the system were affected by the contingency, it is proposed here the use of the following seven performance indexes:

- Angle index.
- Maximum frequency deviation index.
- Total frequency deviation index.
- Dynamic voltage index.
- Quasi-stationary voltage index.
- Power flow index.
- Load shedding index.

4.1.1. Angle index (AI)

Generators usually have protections to avoid asynchronous operation. These protections are generally based on a relay that monitors the impedance observed in the transformer high-voltage bars. Typically this protection is adjusted in such a way that the load angle of the generator (δ_C) does not exceed 120° [11]; otherwise, the relay acts causing the generator to separate from the system. The maximum slip of the load angle offers a suitable security margin since, in case this is not exceeded, the generator may regain its synchronism. The AI is defined by (1):

$$\mathrm{AI} = \min\left\{1,\ \max_{i=1\ldots\mathrm{NG}}\left(\frac{\delta_{\mathrm{c}i,\max}}{\delta_{\mathrm{c},\max,\mathrm{adm}}}\right)\right\} \tag{1}$$

where $\delta_{\mathrm{c}i,\max}$ is the maximum deviation of the load angle of generator i during the simulation time, $\delta_{\mathrm{c},\max,\mathrm{adm}}$ is the maximum admissible load angle for synchronism loss given by the protection relay and NG is the number of generators operating in the system.

4.1.2. Maximum frequency deviation index (MFDI)

The maximum frequency deviation from its rated value is a clear representative of the dynamic effect produced by the contingency analyzed on the system. The higher the maximum frequency deviation the bigger the disturbing effect produced by the contingency. Therefore, an index is proposed that is calculated as the maximum frequency deviation $\Delta f_{i,\max}$ relative to the maximum admissible frequency deviation $\Delta f_{\max,\mathrm{adm}}$. This index ranges from 0 for the case in which no frequency deviation is produced to 1 for the case in which frequency reaches its maximum admissible value, thus indicating the system collapse. The MFDI is defined by (2):

$$\mathrm{MFDI} = \min\left\{1,\ \max_{i=1\ldots\mathrm{NG}}\left[\frac{|\Delta f_{i,\max}|}{\Delta f_{\max,\mathrm{adm}}}\right]\right\} \tag{2}$$

where NG is the number of generators operating on the system. The maximum admissible value is related to the under and over frequency protections of generators, which are set about ±5% of rated frequency. These protections are fundamental to avoid the negative aspects on the auxiliary services and on the generating units related to the increase or decrease of the power system frequency beyond its rated value [12].

4.1.3. Total frequency deviation index (TFDI)

This index stands for the time during which the frequency remained out of its rated value. It is calculated as the quotient between the absolute area of frequency deviation and the maximum admissible area. The range of variation of this index is from 0 for the case in which no variation of frequency occurs all the time, to 1 for the case in which frequency remained at its maximum admissible value all of the simulation time. The TFDI is defined by (3):

$$\mathrm{TFDI} = \min\left\{1,\ \max_{i=1\ldots\mathrm{NG}}\left[\frac{\int_0^{\mathrm{ts}}|\Delta f_i(t)\mathrm{d}t|}{\Delta f_{\max,\mathrm{adm}}\mathrm{ts}}\right]\right\} \tag{3}$$

where $\Delta f_i(t)$ is the temporal deviation of frequency, $\Delta f_{\max,\mathrm{adm}}$ is the maximum admissible frequency deviation, ts is the simulation time, and NG is the number of generators operating on the system.

4.1.4. Dynamic voltage index (DVI)

A requirement that must be met for voltage transients is that at no point in the transport system except during application of the fault in the case of short circuit analysis should the voltage level remain below certain limit [13]. This short circuit case is not dealt with in this work. The dynamic voltage index is related to the requirement mentioned above. The DVI is defined by (4):

$$\mathrm{DVI} = \min\left\{1,\ \max_{i=1\ldots N}\left[\frac{V_\mathrm{n} - v_{i,\min}}{V_\mathrm{n} - v_{i,\min,\mathrm{adm}}}\right]\right\} \tag{4}$$

where $v_{i,\min}$ is the minimum instantaneous voltage on node i during the transient, $v_{i,\min,\mathrm{adm}}$ is the minimum admissible voltage value (0.7 p.u. in this work), N the number of nodes of the system, and V_n the rated voltage.

4.1.5. Quasi-stationary voltage index (QSVI)

This index takes into account the recovery and control of the node voltage at the end of the transient period following the contingency. The index is calculated as the quotient between the voltage deviation at the end of the transient period $\Delta v_{i,\mathrm{aft}}$ (post-contingency voltage deviation on node i) and the maximum voltage deviation limit $\Delta v_{i,\lim}$. The QSVI is defined by (5):

$$\text{QSVI} = \min\left\{1, \max_{i=1\ldots N}\left[\frac{|\Delta v_{i,\text{aft}}|}{\Delta v_{i,\text{lim}}}\right]\right\} \tag{5}$$

where $\Delta v_{i,\text{lim}}$ is a percentage of the rated voltage ($7\% V_\text{n}$ for 500 kV nodes and $10\% V_\text{n}$ for 220 kV nodes).

4.1.6. Power flow index (PFI)

This index takes into account the fact that the power flow after the contingency should not be above the maximum admissible value since an excess of power flow through the lines in the post-contingency steady state may activate the lines protections, thus impairing the system security. The power flow through the transmission lines can be limited due to thermal constraints (it is the case for short transmission lines), or else, due to transient or steady-state stability constraints (this is the case of long transmission lines). The PFI is defined by (6):

$$\text{PFI} = \sum_{i=1}^{\text{NL}} \frac{w_i}{2n}\left(\frac{P_{i,\text{aft}}}{P_{i,\text{lim}}}\right)^{2n} \tag{6}$$

where $P_{i,\text{aft}}$ is the active power flow through the line i at the end of the transient period following the contingency; $P_{i,\text{lim}}$ is the active power flow limit taking into account the strictest restriction (thermal limit, steady-state or transient stability); n is the norm, which is used to reduce the contribution to the PFI index of lines that have not reached their limits; at the same time, this norm is used to amplify the contribution of lines that have exceeded their limits [14]. In this work the norm is taken to be equal to 1; w_i is a weight factor, that is, a real non-negative number, which stands for the relative importance of the lines in the system. In this work, the weight factor is taken to be equal to 1 for all the lines (i.e. all the lines have equal importance). Finally, NL represents the number of transmission lines in the power system.

4.1.7. Load shedding index (LSI)

In order to compensate the load-generation unbalance provoked by the contingency in some extreme cases it is necessary to disconnect load so that the system integrity may be kept. Depending on the magnitude of the unbalance and according to the scheme of automatic load shedding, will be the amount of load disconnected. As an indicator of dynamic security, a load shedding index is proposed. This is calculated as the quotient between the total disconnected load P_shed and the total demand of the system P_total before the contingency. The LSI is defined by (7):

$$\text{LSI} = \frac{P_\text{shed}}{P_\text{total}} \tag{7}$$

4.2. Composing of indexes

The seven performance indexes previously defined are capable of capturing both the dynamic state and the quasi-stationary state of the power system immediately following a contingency. From experience in SSA, it is well known that some indices work better than others for particular power systems and that combination of indices usually work better than a single index [15,16].

The statement to the problem is the following: given the seven calculated performance indexes, it is necessary to compose their effects, in order to count for a single index of dynamic security. This index will reflect the effect that each individual contingency causes to the parameters of the system, and in addition will indicate the distance to the security limit taking in consideration the specific criterion of evaluation defined in this work.

All the performance indexes that take part in the composition are continuous. The composition of several phenomena already has been made in SSA. Nevertheless, there is neither a clear methodology nor a mathematical model to make such composition. On the other hand, the composition requires the combination of several different effects, so, the use of averages or weighted sums would not be adequate.

The occurrence of a contingency modifies the normal operation values of the power system parameters, such as machines angles, frequency, node voltages, and power flow. It is known that the calculated parameters using models of the components of the system are only fair approximations of the real parameters values, and therefore there is an uncertainty associated with these calculated values.

Taking into account the characteristics of the problem, continuous variables and the lack of a mathematical model, it is appropriate to use a FIS for the composition [17]. The FIS provides a robust mathematical framework for modelling the uncertainty associated with the models of the components used and for computing with both linguistic terms and numerical values [18]. In this paper a three-stage FIS is used to compose a fuzzy dynamic security index FDSI. A scheme of these FIS is shown in Fig. 5.

4.2.1. Fuzzy frequency index (FFI)

This index results from the composing of the maximum frequency deviation index MFDI and the total frequency deviation index TFDI by means of the FIS-F. The universe of discourse of the input variables and of the output variable for the FIS-F has been partitioned into three linguistic values: LOW, MEDIUM and HIGH. These variables are equally distributed along the interval [0,1]. Triangular fuzzy sets have been chosen for modelling each linguistic value, because they are naturally associated to the intuitive meaning of "approximately equal to LOW, or MEDIUM, or HIGH". Fig. 6 shows the term set and member-

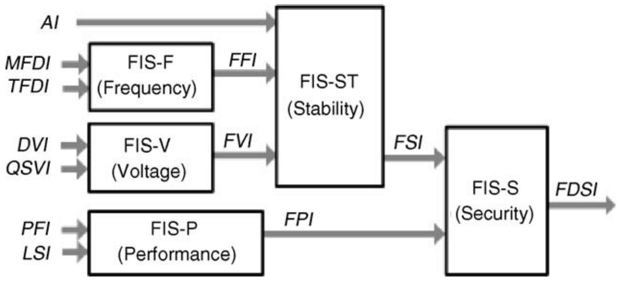


Fig. 5. Three-stage fuzzy inference system.

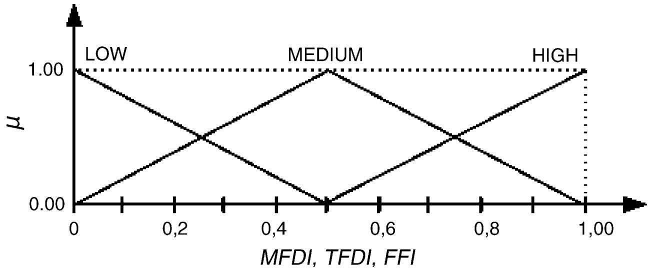


Fig. 6. Term set and membership function for the MFDI, TFDI, FFI.

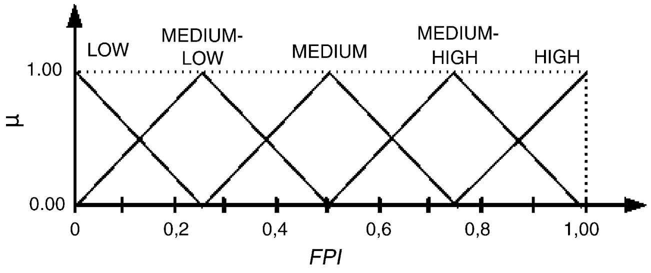


Fig. 7. Term set and membership function for the FPI.

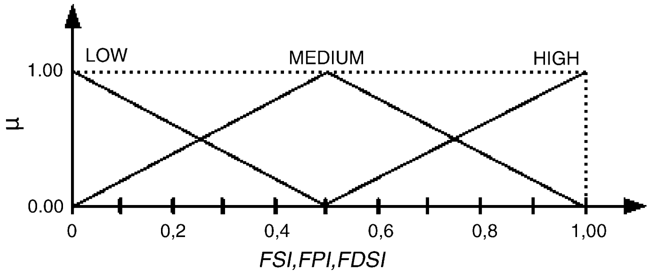


Fig. 8. Term set and membership function for the FSI, FPI, FDSI.

ship functions for the inputs and for the output. The FIS-F uses the rule base of Table 5. Each rule has two antecedents (MFDI and TFDI) and one consequent (FFI). The closer the MFDI or the TFDI is to one, the greater its influence on the FFI. The closer the MFDI and the TFDI is to cero, the smaller its influence on the FFI.

4.2.2. *Fuzzy voltage index (FVI)*

This index results from the composing of the dynamic voltage index DVI and the quasi-stationary voltage index QSVI by means of the FIS-V. The form in which the composition is carried out is identical to the one for the frequency, thus, it is not repeated here.

4.2.3. *Fuzzy performance index (FPI)*

The power flow index PFI and the load shedding index LSI are composed by means of the FIS-P in order to obtain the fuzzy performance index FPI. The universe of discourse of the input variables for the FIS-P has been partitioned into three linguistic values: LOW, MEDIUM and HIGH. The term set and membership function for the PFI and for the LSI are comparable to the inputs variables of the FIS-F. The output of the FIS-P has been partitioned into five linguistic values: LOW, MEDIUM-LOW, MEDIUM, MEDIUM-HIGH and HIGH. These variables are equally distributed along the interval [0,1]. The term set and membership function for the FPI is shown in Fig. 7. The FIS-P uses the rule base of Table 6. Each rule has two antecedents (PFI and LSI) and one consequent (FPI).

4.2.4. *Fuzzy stability index (FSI)*

The fuzzy frequency index FFI and the fuzzy voltage index FVI are composed with the angle index AI on the FIS-ST in order to obtain the fuzzy stability index FSI. The universe of discourse of the input variables and of the output variable has been partitioned into three linguistic values: LOW, MEDIUM and HIGH. These variables are equally distributed along the interval [0,1]. The term set and membership function for the FFI, FVI, AI, and for the FSI are comparable to the one for the FIS-F. The FIS-ST uses the rule base of Table 7. Each rule has three antecedents (FFI, FVI, and AI) and one consequent (FSI).

4.2.5. *Fuzzy dynamic security index (FDSI)*

The fuzzy stability index FSI and fuzzy performance index FPI are composed in the FIS-S in order to obtain the fuzzy dynamic security index FDSI. The universe of discourse of the input variables and of the output variable has been partitioned into three linguistic values: LOW, MEDIUM and HIGH. These variables are equally distributed along the interval [0,1]. Triangular fuzzy sets have been chosen for modelling each linguistic value. Fig. 8 shows the term set and membership functions for the inputs variables and for the output variable.

Table 5
Rule base of FIS-F

Rule number	Antecedents		Consequent
	MFDI	TFDI	FFI
1	LOW	LOW	LOW
2	LOW	MEDIUM	MEDIUM
3	LOW	HIGH	HIGH
4	MEDIUM	LOW	MEDIUM
5	MEDIUM	MEDIUM	MEDIUM
6	MEDIUM	HIGH	HIGH
7	HIGH	LOW	HIGH
8	HIGH	MEDIUM	HIGH
9	HIGH	HIGH	HIGH

Table 6
Rule base of FIS-P

Rule number	Antecedents		Consequence
	PFI	LSI	FPI
1	LOW	LOW	LOW
2	LOW	MEDIUM	MEDIUM_LOW
3	LOW	HIGH	MEDIUM
4	MEDIUM	LOW	MEDIUM_LOW
5	MEDIUM	MEDIUM	MEDIUM
6	MEDIUM	HIGH	MEDIUM_HIGH
7	HIGH	LOW	MEDIUM
8	HIGH	MEDIUM	MEDIUM_HIGH
9	HIGH	HIGH	HIGH

Table 7
Rule base of FIS-ST

Rule number	Antecedents			Consequence
	FFI	FVI	AI	FSI
1	HIGH	HIGH	HIGH	HIGH
2	HIGH	HIGH	MEDIUM	HIGH
3	HIGH	HIGH	LOW	HIGH
4	HIGH	MEDIUM	HIGH	HIGH
5	HIGH	MEDIUM	MEDIUM	HIGH
6	HIGH	MEDIUM	LOW	HIGH
7	HIGH	LOW	HIGH	HIGH
8	HIGH	LOW	MEDIUM	HIGH
9	HIGH	LOW	LOW	HIGH
10	MEDIUM	HIGH	HIGH	HIGH
11	MEDIUM	HIGH	MEDIUM	HIGH
12	MEDIUM	HIGH	LOW	HIGH
13	MEDIUM	MEDIUM	HIGH	HIGH
14	MEDIUM	MEDIUM	MEDIUM	MEDIUM
15	MEDIUM	MEDIUM	LOW	MEDIUM
16	MEDIUM	LOW	HIGH	HIGH
17	MEDIUM	LOW	MEDIUM	MEDIUM
18	MEDIUM	LOW	LOW	LOW
19	LOW	HIGH	HIGH	HIGH
20	LOW	HIGH	MEDIUM	HIGH
21	LOW	HIGH	LOW	HIGH
22	LOW	MEDIUM	HIGH	HIGH
23	LOW	MEDIUM	MEDIUM	MEDIUM
24	LOW	MEDIUM	LOW	LOW
25	LOW	LOW	HIGH	HIGH
26	LOW	LOW	MEDIUM	LOW
27	LOW	LOW	LOW	LOW

Table 8
Rule base of FIS-S

Rule number	Antecedents		Consequence
	FSI	FPI	FDSI
1	LOW	LOW	LOW
2	LOW	MEDIUM	LOW
3	LOW	HIGH	MEDIUM
4	MEDIUM	LOW	MEDIUM
5	MEDIUM	MEDIUM	MEDIUM
6	MEDIUM	HIGH	HIGH
7	HIGH	LOW	HIGH
8	HIGH	MEDIUM	HIGH
9	HIGH	HIGH	HIGH

The AI, the MFDI, the TFDI, the DVI, and the QSVI are calculated considering the maximum and/or minimum admissible values of three parameters of the power systems: angles of the generating machines, system frequency and node voltages. The FIS-ST has been designed so that when anyone of mentioned parameters reaches its maximum and/or minimum value, the output will be equal to one. On the other hand, only when all the inputs are equal to zero, the output of the FIS-ST will be equal to zero.

The PFI is calculated taking in consideration the power flows on the transmission lines in relation with their maximum values. This index represents an “average” of the effect of the considered contingency over the power flows. PFI together LSI compose the FPI, which represents a “combined performance” of the effect that the contingency causes on the power flows and on the amount of load that has been shed.

These previous explanations are made in order to understand the strategy of composition of the FDSI. The FSI is who mainly define the value of the FDSI. The FPI will contribute with a small change to the FSI; change that will increase the value of this last one in case the FPI is great, and will not modify the FSI in case the FPI is small. Table 8 shows the rule base of the FIS-S. Each rule has two antecedents (FSI and FPI) and one consequent (FDSI).

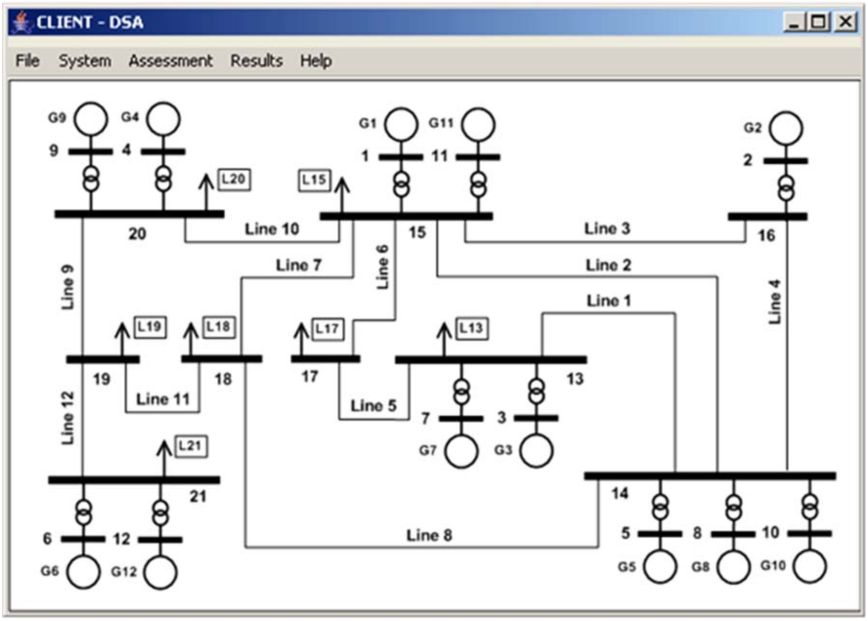


Fig. 9. Grid of 21-node system.

For the five previous FIS, in order to obtain numeric values from the fuzzy sets derived as a result of the inference, the fuzzy mean method is used for defuzzyfication [19].

4.3. Representation of results

In addition to the requirement of determining the security level in a correct and fast way, the dynamic security assessment requires a good representation of the results obtained. In general, when full simulation methods are used there are more options, among others:

- graphs for the different variables in terms of time (voltage, frequency, etc.);
- representation of the results of simulations by means of tables;
- graphic and tabular representation of the dynamic security indexes.

Another important issue in graphic representation is the possibility of having available the grid from the system under analysis. This permits to give an overall picture of the system to those systems operators using the security assessment tool.

The present section is aimed at describing the options offered by the dynamic security assessment program as to representation of the results obtained that are reported in this paper.

4.3.1. Representation of the grid

Fig. 9 shows the main frame of the client program loaded to show as an example the grid of the 21-node power system. This grid contains representation of nodes, transmission lines, voltage step-up transformers, generators and loads.

4.3.2. Tabular representation

As a result of the dynamic security assessment there are available a set of partial indexes and the dynamic security index for each of the contingencies assessed. The client program receives the results from the servers and saves them in an output file for further treatment. In addition, the client program has the option of showing the results obtained in a tabular form. This representation is shown in Fig. 10, which depicts a table containing the various indexes names in the first row and the contingency assessed in the first column. The dynamic security index is shown in the last column. The intermediate columns present the results from the various indexes, both the partial ones calculated as a result of the dynamic simulation as well as those composed of the various levels of the fuzzy inference system.

4.3.3. Graphic representation

This may be quite varied as for example, in bi-dimensional graphs, bar-graphs, etc. Fig. 11 presents a graphic representation of the behaviour of the dynamic security index of the 21-node system for each of the various contingencies. Two different types of bi-dimensional graphs are shown, a rectangular one and a ring-shaped one both for the generators and for the transmission lines outages.

Table 9
Load (MW) of proposed scenarios

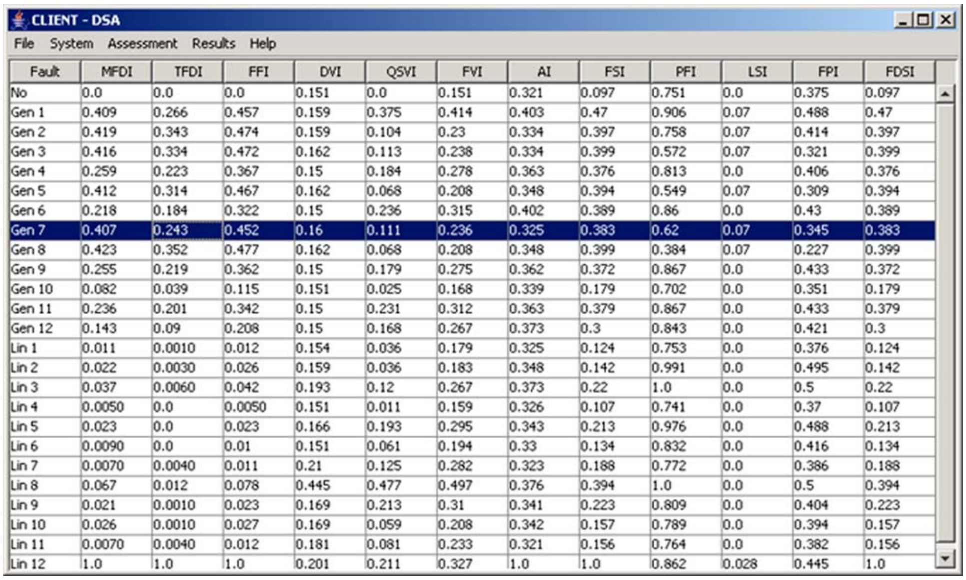
Node	A	B	C
21	133.6	136.3	138.9
22	160.3	163.5	166.7
24	1034.0	1054.7	1075.4
26	62.8	64.1	65.3
27	150.0	153.0	156.0
31	223.9	228.4	232.9
32	47.5	48.5	49.4
34	56.9	58.0	59.2
35	52.0	53.0	54.1
36	214.0	218.3	222.6
37	117.8	120.2	122.5
40	1065.0	1086.3	1107.6
41	417.4	425.7	434.1
42	202.0	206.0	210.1
46	192.7	196.6	200.4
47	158.5	161.7	164.8
49	4.4	4.5	4.6
50	220.2	224.6	229.0
54	1034	1054.7	1075.4
55	24.5	25.0	25.5
57	69.4	70.8	72.2
59	313.5	319.8	326.0
60	21.2	21.6	22.0
61	135.9	138.6	141.3
62	12.4	12.6	12.9
64	83.6	85.3	86.9

Finally, Fig. 12 presents a bar-graph containing all of the contingencies assessed in the 21-node system and the security index value for each of them.

There are various ways of showing the assessment results. Whatever this may be, it is essential for it to be meaningful to the system operator so that he may easily be aware of the security state of the system. In case the system state is insecure the system operator must be able to take the required control actions so as to lead the system to a more secure operation.

5. Application example

A 500 kV power system (reduction of the Argentinean system) was used in order to test the previously explained tool. The characteristics of this system are the following (Fig. 13): it has 65 nodes, 45 transmission lines, 18 generating units, 18 step-up transformers and 26 loads. By the system reduction some units with the same characteristics are represented through a dynamic equivalent unit. Further details of the system data are not shown due to space limitations. To verify the effectiveness of the developed tool, three scenarios are proposed in which the dynamic security indexes are calculated. Each of these scenarios has a different load condition. The idea is to prove the efficiency of the tool on a base scenario and to compare it with the results obtained in various scenarios where the system is under greater stress. Each scenario has 2% of additional load with respect to the previous one, starting from scenario A. The additional load on the scenarios B and C has been uniformly distributed in the nodes with load on base scenario A (see Table 9). These values are taken on the pre-contingency state. Table 10 shows



Fault	MFDI	TFDI	FFI	DVI	QSVI	FVI	AI	FSI	PFI	LSI	FPI	FDSI
No	0.0	0.0	0.0	0.151	0.0	0.151	0.321	0.097	0.751	0.0	0.375	0.097
Gen 1	0.409	0.266	0.457	0.159	0.375	0.414	0.403	0.47	0.906	0.07	0.488	0.47
Gen 2	0.419	0.343	0.474	0.159	0.104	0.23	0.334	0.397	0.758	0.07	0.414	0.397
Gen 3	0.416	0.334	0.472	0.162	0.113	0.238	0.334	0.399	0.572	0.07	0.321	0.399
Gen 4	0.259	0.223	0.367	0.15	0.184	0.278	0.363	0.376	0.813	0.0	0.406	0.376
Gen 5	0.412	0.314	0.467	0.162	0.068	0.208	0.348	0.394	0.549	0.07	0.309	0.394
Gen 6	0.218	0.184	0.322	0.15	0.236	0.315	0.402	0.389	0.86	0.0	0.43	0.389
Gen 7	0.407	0.243	0.452	0.16	0.111	0.236	0.325	0.383	0.62	0.07	0.345	0.383
Gen 8	0.423	0.352	0.477	0.162	0.068	0.208	0.348	0.399	0.384	0.07	0.227	0.399
Gen 9	0.255	0.219	0.362	0.15	0.179	0.275	0.362	0.372	0.867	0.0	0.433	0.372
Gen 10	0.082	0.039	0.115	0.151	0.025	0.168	0.339	0.179	0.702	0.0	0.351	0.179
Gen 11	0.236	0.201	0.342	0.15	0.231	0.312	0.363	0.379	0.867	0.0	0.433	0.379
Gen 12	0.143	0.09	0.208	0.15	0.168	0.267	0.373	0.3	0.843	0.0	0.421	0.3
Lin 1	0.011	0.0010	0.012	0.154	0.036	0.179	0.325	0.124	0.753	0.0	0.376	0.124
Lin 2	0.022	0.0030	0.026	0.159	0.036	0.183	0.348	0.142	0.991	0.0	0.495	0.142
Lin 3	0.037	0.0060	0.042	0.193	0.12	0.267	0.373	0.22	1.0	0.0	0.5	0.22
Lin 4	0.0050	0.0	0.0050	0.151	0.011	0.159	0.326	0.107	0.741	0.0	0.37	0.107
Lin 5	0.023	0.0	0.023	0.166	0.193	0.295	0.343	0.213	0.976	0.0	0.488	0.213
Lin 6	0.0090	0.0	0.01	0.151	0.061	0.194	0.33	0.134	0.832	0.0	0.416	0.134
Lin 7	0.0070	0.0040	0.011	0.21	0.125	0.282	0.323	0.188	0.772	0.0	0.386	0.188
Lin 8	0.067	0.012	0.078	0.445	0.477	0.497	0.376	0.394	1.0	0.0	0.5	0.394
Lin 9	0.021	0.0010	0.023	0.169	0.213	0.31	0.341	0.223	0.809	0.0	0.404	0.223
Lin 10	0.026	0.0010	0.027	0.169	0.059	0.208	0.342	0.157	0.789	0.0	0.394	0.157
Lin 11	0.0070	0.0040	0.012	0.181	0.081	0.233	0.321	0.156	0.764	0.0	0.382	0.156
Lin 12	1.0	1.0	1.0	0.201	0.211	0.327	1.0	1.0	0.862	0.028	0.445	1.0

Fig. 10. Tabular representation.

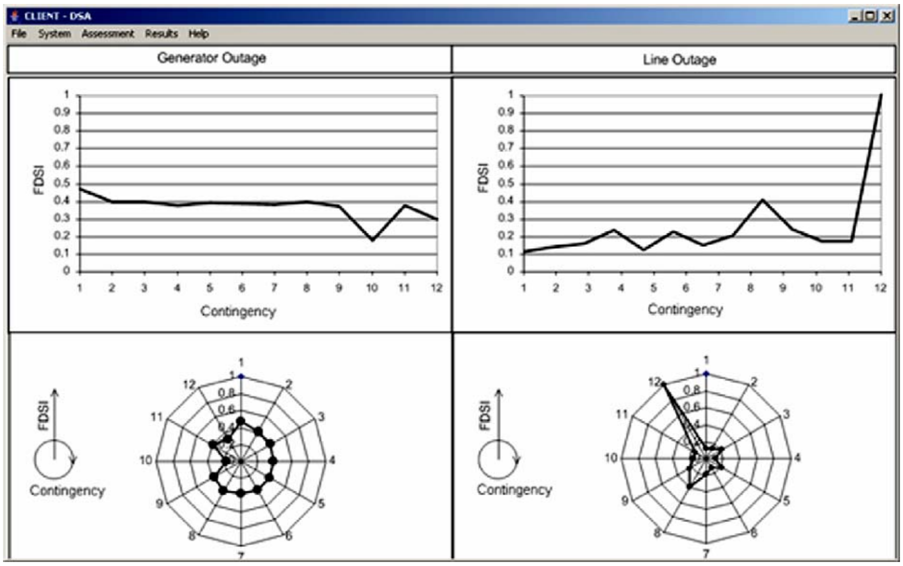


Fig. 11. Graphic representation.

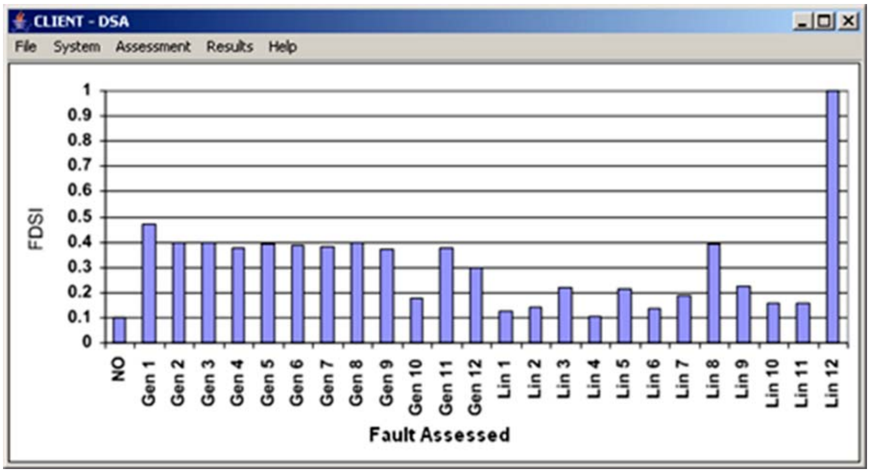


Fig. 12. Representation by graph-bar.

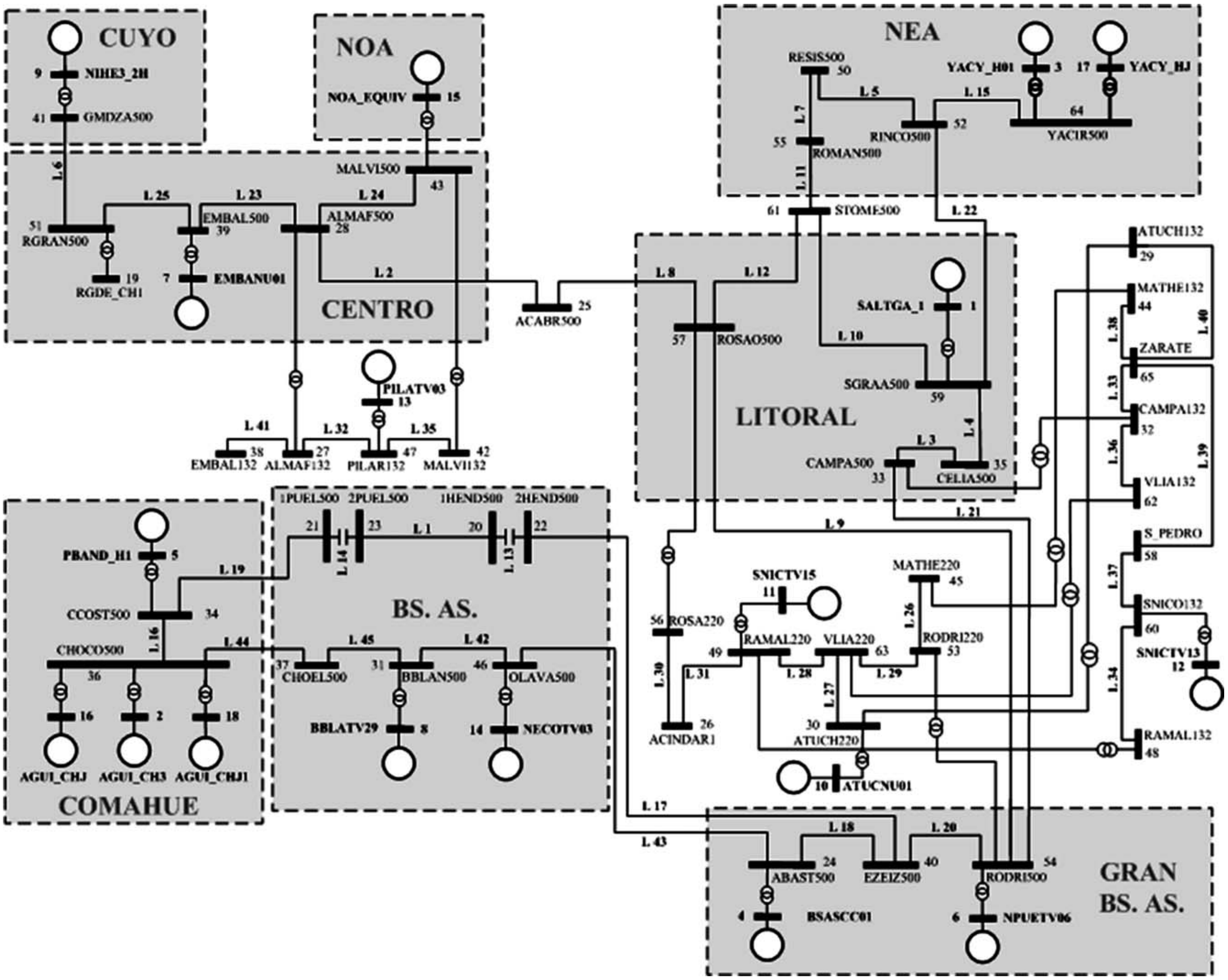


Fig. 13. Grid of Argentinean power system.

Table 10
Generation power (MW) of proposed scenarios

Gen	A	B	C
1	243.4	248.3	253.1
2	644.8	657.7	670.6
3	1610	1642.2	1674.4
4	313.2	319.5	325.7
5	569	580.4	591.8
6	226.6	231.1	235.7
7	573.7	585.2	596.6
8	441.6	450.4	459.3
9	284.7	290.4	296.1
10	298.5	304.5	310.4
11	277	282.5	288.1
12	90.5	92.3	94.1
13	32	32.6	33.3
14	60.6	61.8	63.0
15	86.9	88.6	90.4
16	350	357.0	364.0
17	155	158.1	161.2
18	250	255.0	260.0
Total	6507.5	6637.65	6767.8

the power delivered by each one of the generating units and the total power generated in each scenario, from the pre-contingency state. Table 11 shows the absolute value of the active power flowing through each one of the transmission lines in each scenario. These values are taken in the pre-contingency state.

The results obtained from calculation of the fuzzy dynamic security indexes (FDSI) for the three scenarios are shown in Table 12 for the cases: no contingency, generator outages and transmission line outages. Short circuit analysis for transmission lines is not included because of the very small values of FDSI. This outcome is the result of the transmission protection equipments, which work separating them in case of failures. In other words, the system is prepared to hold such events without major problems. Furthermore, and given the radial nature of the Argentinean transmission system, the complete loss of a major interconnection line is a much more severe event. The calculated performance indexes for the case without contingency are the expected ones, thus indicating a normal operation state of the system. It is important to note how much the FDSI increases in the scenarios where the system is under greater stress. Similar to this occurs for generator outages and transmission line outages, regarding same case where the FDSI is

Table 11
Active power flow (MW) of the pre-contingency state

Line	A	B	C
1	940.0	957.9	975.8
2	42.8	43.7	44.5
3	517.5	529.6	541.5
4	574.8	588.2	601.5
5	812.0	827.0	842.0
6	134.1	136.7	139.4
7	583.1	593.2	603.4
8	42.5	43.3	44.1
9	519.0	529.1	539.9
10	56.9	60.4	63.8
11	550.0	559.9	569.1
12	471.3	481.3	491.2
13	917.9	934.7	951.6
14	940.0	957.9	975.8
15	1672.5	1708.5	1742.0
16	579.9	590.6	601.4
17	757.6	771.2	784.9
18	325.3	331.6	337.7
19	1088.5	1109.4	1130.4
20	643.5	675.8	672.0
21	551.1	563.7	576.2
22	809.1	824.8	840.4
23	437.4	446.3	454.9
24	171.6	174.9	178.2
25	134.2	136.8	139.6
26	43.2	44.2	45.1
27	237.5	242.2	246.8
28	157.7	161.2	164.8
29	347.4	354.6	361.8
30	78.5	79.4	80.5
31	141.6	143.8	146.1
32	72.9	74.6	76.1
33	53.2	54.3	55.3
34	29.2	29.7	30.2
35	55.9	56.9	57.9
36	30.6	31.2	31.7
37	39.3	40.2	41.1
38	43.2	44.2	45.1
39	38.6	39.5	40.4
40	59.2	60.4	61.6
41	0.0	0.0	0.0
42	532.6	543.7	554.9
43	395.7	403.8	412.2
44	442.9	452.5	462.1
45	321.9	329.0	336.2

Table 12
Dynamic security index

No	A	B	C
0	0.01	0.02	0.03
Gen	A	B	C
1	0.19	0.16	0.47
4	0.25	0.61	1.00
5	0.34	0.35	1.00
6	0.16	0.60	1.00
7	0.50	0.48	0.47
8	0.33	0.33	1.00
9	0.31	0.35	0.39
10	0.18	0.19	0.47
11	0.18	0.18	0.19
12	0.07	0.09	0.11
13	0.08	0.08	0.08
14	0.10	0.10	0.10
15	0.15	0.15	0.15
16	0.25	0.26	0.28
17	0.14	0.15	0.16
18	0.16	0.17	0.19
Line	A	B	C
18	0.35	0.48	1.00
21	0.64	1.00	1.00
24	0.85	0.85	1.00
26	0.02	0.03	0.04
27	0.15	0.57	1.00
28	0.04	0.05	0.07
29	0.09	1.00	1.00
30	0.13	0.13	0.13
31	0.14	0.14	0.48
32	0.95	0.95	1.00
33	0.02	0.03	0.04
34	0.10	0.10	0.10
35	0.06	0.06	0.07
36	0.02	0.03	0.03
37	0.03	0.03	0.04
38	0.01	0.02	0.03
39	0.02	0.03	0.04
40	0.03	0.03	0.04
41	0.01	0.02	0.03
44	0.54	1.00	1.00

greater in previous scenarios due to the no linear behaviour of the power systems, for example outage of generator 1 or 7.

The outage of lines 1–17, 19, 20, 22, 23, 25, 42, 43, and 45 result in a FDSI equal to 1 on the three scenarios; for this reason they are not shown in Table 12 in order to save space. Any of these contingencies causes huge frequency excursion, important voltages dip and large machines angles deviation. The fault of any line 19, 1, or 17, provokes the loss of one tie between nodes 34 and 40, which are generation and consumption nodes respectively. Therefore, the ties not failed could not transport the total pre-contingency power flow from node 34 to node 40. The same occurs with the outage of lines 44, 45, 42, or 43, which affects the path between nodes 36 and 24. In both cases result a great power deficit in the area GRAN BS AS. Similar situations present the remaining lines that transport important power flow between generation and consumption areas. In case the outage occurs on lines 6, 25, 23, 2, or 8, the system is separated in islands and then FDSI becomes a value equal to 1.

For all cases with equivalent generating units, there is one unit out of the equivalent. That way, only the FDSI of that unit is calculated; e.g. units 16, 17, and 18 in Fig. 13.

In general it is possible to conclude that in the Argentinean power system the transmission lines outages are more dangerous than the generators outages. The calculated FDSI clearly shows this tendency. The reason thereby stems in the structure of the system: radial network with consumption areas far away from generation areas, which makes necessary the power transport through heavy loaded long transmission lines.

6. Conclusions

To get a complete online DSA of power systems nowadays represents an increasingly more complex challenge for system operation. The DSA calculating tool presented in this paper proposes a new approach that uses fuzzy logic together with distributed processing of existing power system analysis tools in order to enhance the capabilities of online security assessment. The proposed DSA is based on the evaluation of the post-disturbance behaviour of the system through defined performance indexes, which are composed in one fuzzy dynamic security index. Following advantages are achieved by the developed DSA calculation tool:

- the distributed processing of the dynamic simulations makes unnecessary the use of approximate methods to reduce the calculation time;
- the software implementation in Java language makes possible to generate a tool based on open architecture that gives independence from the hardware manufacturer;
- the use of PCs interconnected by means of a LAN-type network permits a low-cost implementation;
- calculation of the different partial performance indexes and their composition in a sole fuzzy dynamic security index ensures a full assessment of the operation state of the system taking into account various aspects related to the system security level, as well as to clearly and simply represent the results of the complete DSA;
- the developed tool may show to system operators not only the final fuzzy dynamic security index, but also the seven performance indexes and the other four fuzzy composed indexes;
- the fuzzy inference systems have the advantage that the output in each of them is almost instantaneous. This is due to the fact that evaluating the rules of their knowledge bases is not a time-consuming task;
- it is important to remark that the seven calculated performance indexes are based on full time-domain simulations, not using approximate methods or accelerated time-domain simulators;
- the tool for online inference of DSA is “easy to use” and “easy to understand”. Also it is possible that the system operators can modify the rule base of each FIS, on the basis of their experience in the operation of the power systems;
- both the distributed processing of the dynamic simulations and the indexes composition tool based on fuzzy logic considerably reduce the calculation time required, which makes possible the implementation of an online assessment of the dynamic security.

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