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DSA-Visualisation Monitoring and Ranking of System Dynamic Behaviour

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Abstract: The paper presents the application of a software tool to simulate system dynamic behavior together with the possibility to select critical contingencies of an electrical energy system. These cases are visualized and a ranking decision is introduced to support the operators to select critical system states. Insecure operating conditions can be monitored in the time domain using the full system representation in real time or by calculating the eigenvalues of the system to monitored weakly damped system states and stability margins.

1. INTRODUCTION

All over the world electrical systems are growing or will be interconnected to allow new economic objectives for operation. With open access to deregulated markets the power transfers are forcing the transmission systems to their limits. To achieve higher economic objectives the systems are again operated closer to their limits. As a result unexpected events, weak interconnections, high loading of lines and corridors or hidden protection failures may cause the systems to loose stability – possibly leading to catastrophic failures or black-outs. In the last years the numbers of black-outs and their negative consequences have been grown. Analyzing these catastrophes show that for years operating guidelines have been used based on off-line stability studies, which tend to be conservative for normal conditions and inaccurate for unexpected unusual events. Oscillations and dynamics can compromise grid reliability and poorly understood dynamic constraints can unnecessarily narrow system limits. The complexity of large electrical systems with different primary and secondary control mechanisms, operation with economic objectives, use of extremely fast acting FACTS devices and fast change of load flow and last but not least complex protection philosophies can not be represented using static security assessment. In addition electrical markets are changing from vertically integrated structures with centralized competence to competitive deregulated structures, where electrical market is driven by economy and needs higher automatic security assessment.

In many cases a static security assessment can not achieve the necessary security under changing grid and generation conditions. The need for real time assessment of dynamic stability (DSA) was high-lighted by the black-outs 2003 in USA and Italy: the Italy black-out started with 6545 MW import to Italy; cascading phenomena isolated the Italian system from Europe; loss of generation in Italy and insufficient load shedding drove the system to be black. The phenomenon occurred in less than 3 minutes, but it has been proceeded by about 15 minutes within which the problem has evolved from a normal situation to an alert and then to an emergency state with a restoration time of abnormally 19 hours. A list of evolving factors has been collected from which the improved power system monitoring and preventive actions are the most important items.

Other factors which affect system security are significant changes in generation in deregulated markets. Combined cycle power plants and distributed generation reduce the controllability, wind farms located not related to load centres affect the system security through the changing wind availability. New security analyzing systems have to take this system behaviour into account.

2. DYNAMIC SECURITY ASSESSMENT - OPERATIONAL STATES

The security of an electrical system can be predicted based on the evaluations of load, operational and security constraints. The evaluation of the critical constraints is an essential key function to predict how secure the system is in actual or future state. A system is insecure if, following a contingency, the constraints of the system can not be fulfilled. Fig. 1 shows the different states of a system. Only if the system does not lead to an emergency or restoration state after contingency the system is secure.

By preventive measures the system can be controlled to stay or come back to a normal and secure state. In addition an emergency and restoration strategy are necessary after severe fault to guarantee a save system operation.

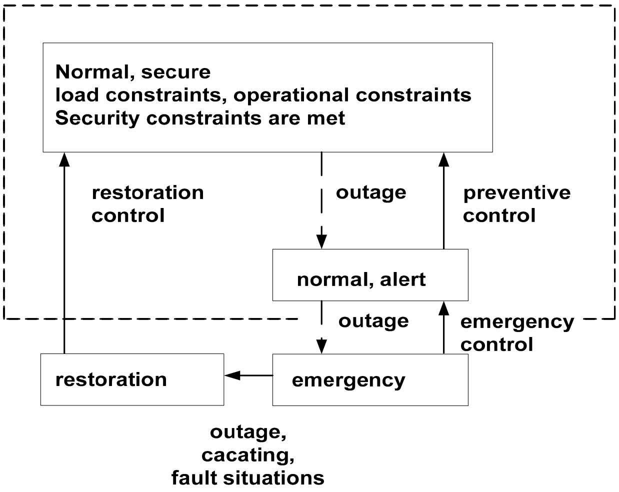


Fig. 1. Operational states of a power system

3. SYSTEM CONSTRAINTS

A system has to be operated in accordance with the system

- load constraints
- operational constraints
- security constraints

The requirements for a DSA are to prove whether the system fulfils the constraints after outages or severe system faults under different system states. Main constrains of a system are margins to thermal limits, margins to loading limits and margins to stability limit. The constraints can be expressed by concrete criteria like critical under/overvoltages, critical loading of lines, critical under/overfrequencies or critical angle differences between generators or system areas.

A DSA system has to be able to cover these constraints and show the operators the “distance” to the dangerous system stages by reporting the system margins.

4. STRUCTURE OF A DSA SYSTEM

A flexible DSA system is shown in fig. 2, which allows to select different load flow situations (scenarios) using the base topology of the system. A contingency builder is used to select individual contingencies in an automatic process. The contingencies are checked using selected criteria which are defined by a criteria builder. The system checks the security criteria like stability, overcurrent, under-/overfrequency, stability, damping etc. These criteria can be combined individually to define a suitable set of criteria to describe the constraints of the system.

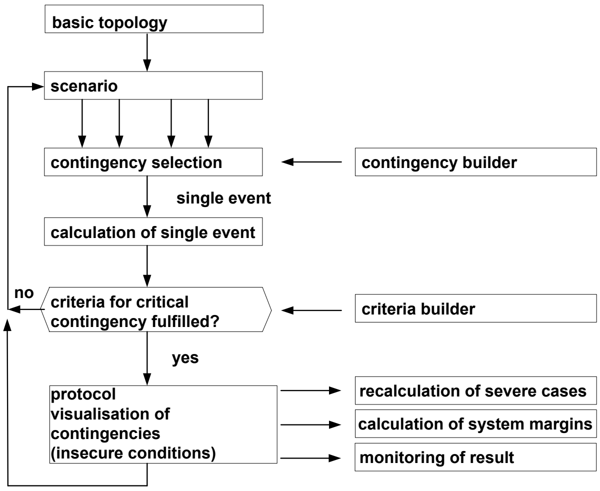


Fig. 2. Structure of the DSA system

Fig. 3. shows the structure of the criteria builder, which allows to build individual criteria and combinations of criteria which have to be checked. As a secondary task the criteria builder prepares the visualisation and re-calculation of cases of interest. These re-calculations sorts the results either by criteria (undervoltage, overcurrent, etc.) or by network elements (generator, line, etc.).

The sorting mode allows the user to select defined visualisation and to compare them.

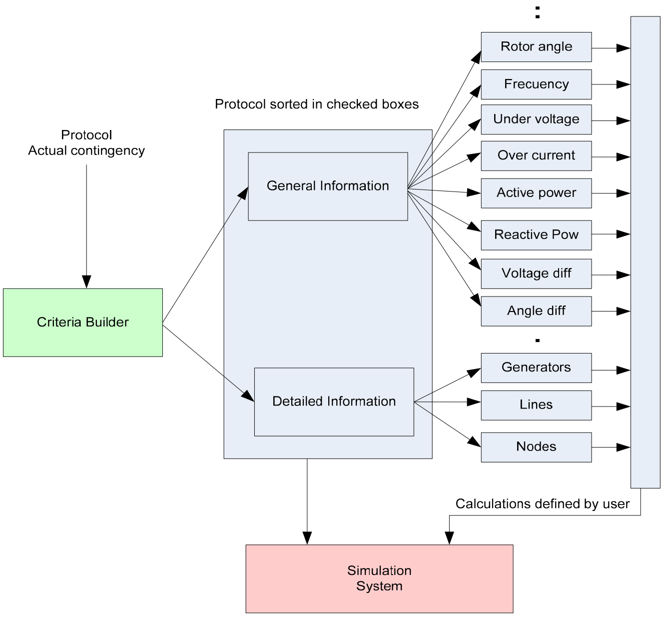


Fig. 3. Re-calculation part of criteria builder – secondary tasks

The DSA documents the contingencies when the system limits are exceeded (reaching generator stability, voltage below 80 %, angle difference between two nodes larger than 40°, etc.). These cases can be recalculated very easily. All necessary characteristics can be visualized to get a deeper view for the operator. In parallel the critical contingencies are monitored.

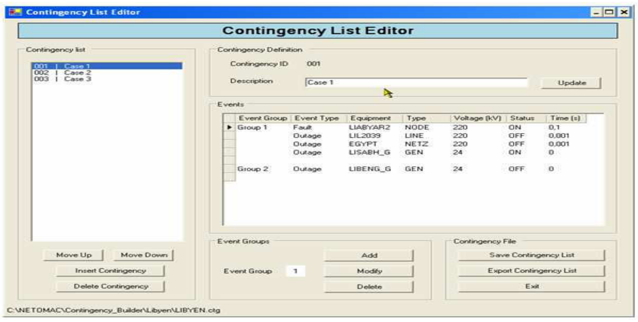
5. DYNAMIC SECURITY ASSESSMENT USING A MODERN SIMULATION TOOL

Because of the individual character of an electrical system DSA has to be flexible to simulate all important system components representing the passive grid equipment (lines, cables, transformers, etc.) and the active switching or control elements (capacitor banks, FACTS devices etc.) together with their control schemes. For cascading faults important protection devices have to be activated in the simulation. All important contingencies have to be simulated using a simple contingencies building process. The decision criteria have to be flexible, user defined and are adapted to describe critical limits of the system. The DSA presented here was built based on a general simulation packages for electromechanical time simulations with a module to calculate small signal stability (eigenvalue analysis), too. The PSS™NETOMAC simulation system was selected to be the calculation base of the DSA (see internet).

The time domain simulation allows the most accurate description of the system from transient stability to voltage collapse. The DSA provides the analysis of dozens of contingencies per minute, based on the actual state of the system, and potential system failures. A typical demand per single processor computer system is 10 load flow cases with about 20 main contingencies checked and reported in 10 minutes.

The program system used for the DSA fulfils this computation speed demand as the example in chapter 8 proves. In addition the use of eigenvalue analysis allows having a specific view on system interarea oscillation and damping, too. The simulation tool is structured to be used as a DSA system, importing data from the EMS and using user defined contingency and security criteria. Preventive measure design and test can be incorporated in the DSA to support the operator finding countermeasures in case of critical system situations.

Fig. 4 shows the typical user interface to create the contingencies which shall be investigated. The contingency builder allows to select grid elements, equipment and events and combination of them to write a scenario file. The security criteria builder defines the criteria and combination which the user has defined to be representative for the system security.



Contingency List Editor

001 | Case 1
002 | Case 2
003 | Case 3

Contingency ID 001
Description Case 1

Event Group	Event Type	Equipment	Type	Voltage (kV)	Status	Time (s)
Group 1	Fault	LIABYAR2	NODE	220	ON	0,1
	Outage	LIL2039	LINE	220	OFF	0,001
	Outage	EGYPT	NETZ	220	OFF	0,001
	Outage	LISABH_G	GEN	24	ON	0
Group 2	Outage	LIBENG_G	GEN	24	OFF	0

Event Group 1

C:\NETOMAC\Contingency_Builder\Libyen\LIBYEN.ctg

Reading: data input file

Selections:
- Elements
- Equipment
- Events

Selection-Criteria:
- „all“
- „selected“
- „combined“
- Areas
- Voltage levels
- ...

Writing: scenario files

Fig. 4. Snapshot of the contingency builder

6. VISUALISATION AND MONITORING

The human being is able to process and analyse visual information, because an overview for a complex situation is easier understood. With the help of graphical representation as voltage-current- or power flow-profiles it is easier possible to recognize in a short period of time the weakest points in a system, which allows to establish preventive measures to avoid undesirable situations. Several possibilities to find a better system understanding have been established like numerical visualisations, detailed re-calculations, bar animation, vector animation and matrix & electrical diagram representation. Fig. 5 shows some of the possibilities to visualize the system behaviour.

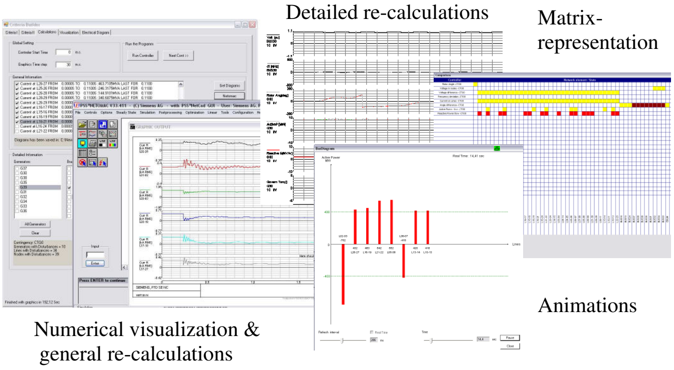


Fig. 5. Visualization and monitoring of the dynamic behaviour of power systems in case of system contingencies

The matrix representation (Fig. 6) allows organizing the contingencies and criteria automatically by a colour scale (sorted by contingency, criteria and related network element).

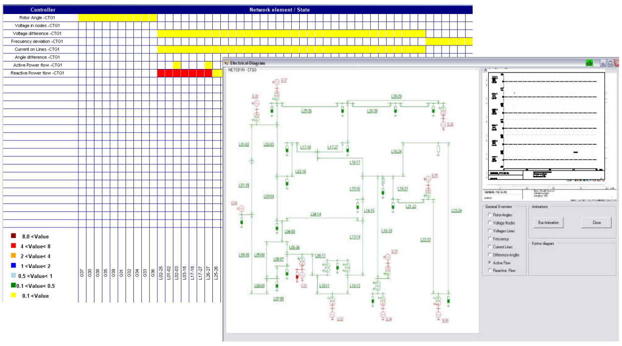


Fig. 6. Matrix & electrical diagram representation

The electrical diagram representation (Fig. 6) allows looking detailed in the time behaviour at selected system nodes and branches.

7. INDICES FOR CONTINGENCY SCREENING AND RANKING

In addition to the direct criteria specific indices are calculated to define how secure a system state or a system contingency can be. These criteria are for example (see References)

- change of rotor angle differences
- change of rotor angle differences with respect to centre of inertia
- change of voltage an currents
- change of generator speed or system frequency
- change of transient energy of generators
- acceleration of generators
- system oscillation and damping

There are several other indices which have been established in the DSA (see References).

7.1 Indices based on dot products (DP)

One way of ranking is to use a set of indices based on a dot product. A dot product is defined for detecting the exit point in the transient energy function (TEF). The exit point is characterized by the first maximum of transient potential energy with respect to the post-fault network. It is computed by the dot product of the fault-on mismatch vector and the fault-on speed vector as given by (3).

$$dot1 = \sum_{i=1}^{NG} f_i \cdot \omega_i \qquad (1)$$

$$fi = P_{mi} - P_{ei} - \frac{M_i}{M_t} \cdot P_{COI} \qquad (2)$$

$i = 1,2,.....,NG$

$$P_{COI} = \sum_{i=1}^{NG} (P_{mi} - P_{ei}) \qquad (3)$$

where:

Mi: inertia constant of each generator
Mt: total inertia constant of all generators
P_{mi}: mechanical power input of each generator
Pei: electrical power output for each generator
ω_i: rotor speed with respect to COI

The dot product gives the measure of total accelerating power and the power system (including generator and network) response to this accelerating power, thus it is an adequate index for ranking dynamic contingencies. In addition, based on the vector of rotor angle two additional dot products are defined (4, 5).

$$dot2 = \sum_{i=1}^{NG} f_i \cdot \Theta_i \qquad (4)$$

$$dot3 = \sum_{i=1}^{NG} \omega_i \cdot \left(\Theta_i - \Theta_i^{cl}\right) \qquad (5)$$

where:

Θ_i: rotor angles with respect to COI

Θ_i^{cl}: rotor angle of *i*th generator at fault clearing time

7.2 Angle index (AI)

The AI is defined as a minimum between 1 and maximum ratio of maximum deviation of the load angle of *i*th generator and the maximum admissible load angle given by the protection relay (6). Namely, the relays, protecting the generator against asynchronous operation, are adjusted in such a way that the load angle of the generator (δ_i) does not exceed a certain value (e.g. 120°).

$$AI = \min\left\{1, \max_{i=1,...NG}\left(\frac{\delta_{ci,\max}}{\delta_{c,\max,adm}}\right)\right\} \qquad (6)$$

7.3 Maximum frequency Deviation Index (MFDI)

The index is calculated as the maximum frequency deviation $\Delta f_{i,\max}$ relative to the admissible frequency deviation $\Delta f_{i,\max,adm}$ (7). It 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. The maximum admissible value is related to the under- and over-frequency protection of generators.

$$MFDI = \min\left\{1, \max_{i=1,...NG}\left[\frac{\left|\Delta f_{i,\max}\right|}{f_{\max,adm}}\right]\right\} \qquad (7)$$

7.4 Total Frequency Deviation Index (TFDI)

The index stands for the time during which the frequency remained out of its rated value. It is defined as the quotient between the absolute area of frequency deviation and the maximum admissible are. The range is from 0 to 1 respectively to the case of no frequency variation and the case in which frequency remained at its maximum admissible value all the simulation time. The index is given by (8) where $\Delta fi(t)$ is the temporal frequency deviation, $\Delta f_{\max,adm}$ is the maximum admissible frequency deviation, t_s is the simulation time and NG number of generators.

$$TFDI = \min\left\{1, \max_{i=1,...NG}\left[\frac{\int_0^{ts}\left|\Delta f_i(t)\right|dt}{\Delta f_{\max,adm} ts}\right]\right\} \qquad (8)$$

7.5 Dynamic Voltage Index (DVI)

The dynamic voltage index is based on requirement 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. In (9), the $v_{i,\min}$ is the minimum instantaneous voltage, $v_{i,min,adm}$ is the minimum admissible voltage, V_n the rated voltage and N number of nodes.

$$DVI = \min\left\{1, \max_{i=1,\dots N}\left[\frac{V_n - v_{i,\min}}{V_n - v_{i,\min,adm}}\right]\right\} \quad (9)$$

7.6 Quasi-Stationary Voltage Index (QSVI)

The index addresses the recovery and control of the node voltage at the end of the transient period following the contingency. It is calculated as the quotient between the post-fault voltage deviation $\Delta v_{i,aft}$ and the maximum voltage deviation limit Δvi,lim, where the latter is the percentage of the rated voltage.

$$QSVI = \min\left\{1, \max_{i=1,\dots N}\left[\frac{\Delta v_{i,aft}}{\Delta v_{i,\lim}}\right]\right\} \quad (10)$$

7.7 Power Flow Index (PFI)

The index takes into account the post-fault power flow since its excess may activate the line protection. The power flow through transmission lines can be limited due to thermal limits (for lines up to 80km), voltage drop limit (for lines between 80 and 320km), or stability limits (for lines longer than 320km). The index is defined by (11), where $P_{i,aft}$ is the post-fault power flow through *i*th line; $P_{i,lim}$ is the power-flow limit taking into account the strictest restriction (thermal limit, voltage drop or stability limit), n is the norm used to reduce/ amplify the contribution of the PFI index of lines that have not reached/ have reached their limits, and ωi is the weight factor which stands for the relative importance of the lines in the system. NL is the number of lines.

The value 1 of this index represents that at least in one line of the system the power flow reaches it limit.

$$PFI = \frac{1}{NL}\sum_{i=1}^{NL}\omega_i\left(\frac{P_{i,aft}}{P_{i,\lim}}\right)^n, \ if\ P_{i,aft} < P_{i,\lim}\ \forall i \quad (11)$$

$$PFI = 1, if\ \exists\ P_{i,aft} \geq P_{i,\lim} \quad (12)$$

7.8 Load Shedding Index (LSI)

The LSI (13) index is calculated as the quotient between the total disconnected load P_{shed} and the total demand of the system P_{total} before the contingency. It defines the amount of the load to be disconnected in the load-shedding sequence in order to keep the system's integrity.

$$LSI = \frac{P_{shed}}{P_{total}} \quad (13)$$

7.9 Fuzzy Dynamic Security Index (FDSI)

The composite index is calculated using a cascading three stage fuzzy inference system (FIS) illustrated in figure 7. The FIS composes the FDSI by using three linguistic values LOW MEDIUM and HIGH, which describe index input/output variables equally distributed along the interval [0, 1]. Example of joining the indices using the technique is provided in table 1.

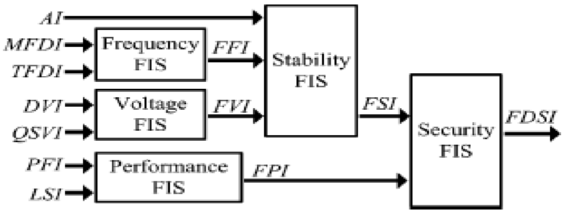


Fig. 7. Cascading three stage FIS

Table 1. Output rules of FSI

Rule No.	Antecedents FSI	Antecedents FPI	Consequent FDSI
1	LOW	LOW	LOW
2	LOW	MEDIUM	LOW
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

8. EXAMPLE: THE EUROPEAN INTERCONNECTED SYSTEM

The European UCTE system was used to demonstrate the performance of the DSA. The system today has an installed capacity of about 530 000 MW (2004) with a maximum load demand of about 386 000 MW (2004). A model of the system was built with 610 generators, 4400 nodes, 12000 grid branches, 1050 controllers. The system model was tested using measurements of the installed WAMS. Fig. 8 shows, the measured interarea oscillation after trip of a 300 MW power station (Fig. 8a) and the simulation of the event for 15 seconds (Fig. 8b). The results demonstrate that the model represents the overall electromechanical system behavior.

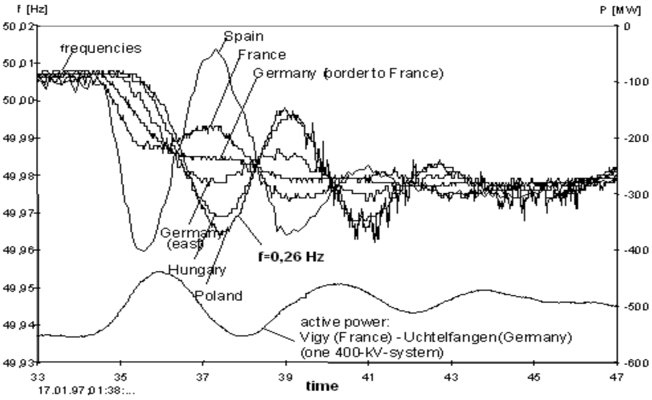


Fig. 8a. Measurement of a power oscillation after 300 MW trip

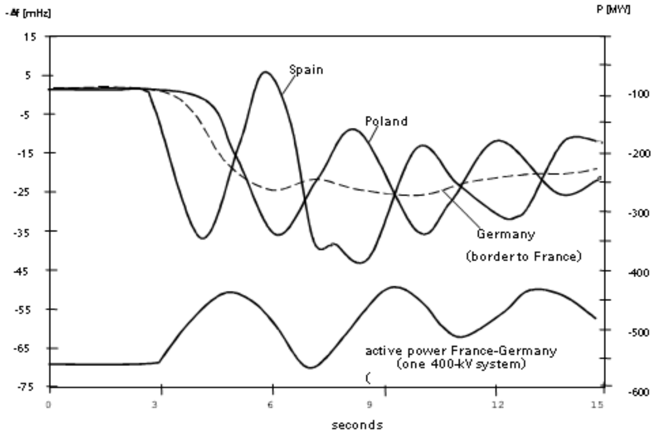


Fig. 8b. Simulation of a 300 MW trip

Fig. 9 depicts that time steps of 10 ms are the limit to run the system under real time conditions. For the electromechanically behaviour the accuracy with time steps of 20 – 50 ms is suitable.

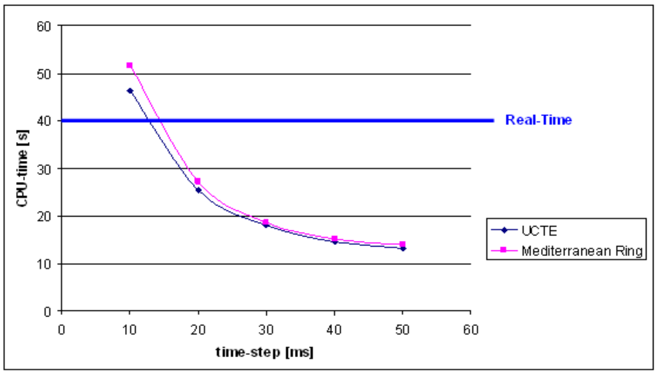


Fig. 9. Simulation results and computation time

Using the eigenvalue mode of the system the interarea oscillations of the system can be easily monitored and the system shows how and which generators are involved in the oscillation (Fig. 10).

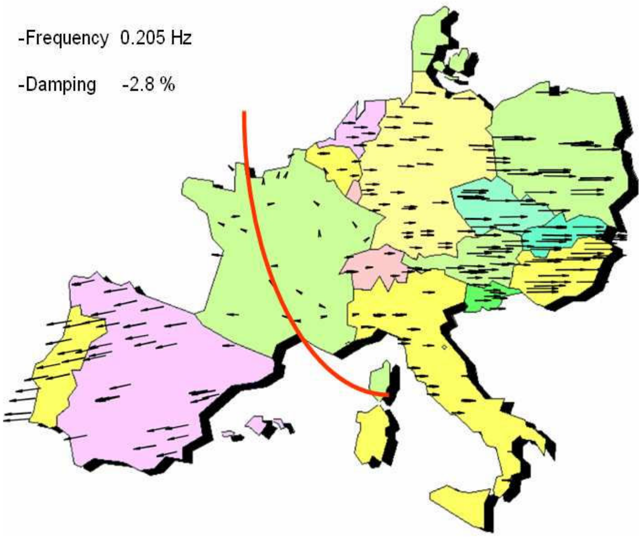


Fig. 10. Monitoring of geographical mode shape of an interarea oscillation in the UCTE system (Spain oscillates against Central Europe and the CENTREL Counties)

Because of the flexible change from time domain to frequency domain calculation remedial actions and preventive measures are easily built in and can be tested in real time.

9. CONCLUSION

The evolving nature of the power industry under changing conditions to economic driven deregulated markets has made on-line security assessment a critical function-essential component in ensuring reliability. The paper shows how a powerful simulation system can be used to built a system and user oriented DSA which includes contingency building, security criteria selection, computation, reporting/visualization and ranking to support the operators to understand the complex structure of electrical systems. The use of the contingency builder, a flexible criteria creator to identify critical contingencies, a ranking system and a flexible reporting allow the user to customize the DSA for the system where it will be used. The example of a very large electrical system proves the real time opportunities of the system.

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