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Faster than Real Time: Dynamic Security Assessment for Foresighted Control Actions

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Abstract-- **In this paper, implementation of power system dynamic security assessment (DSA) into real time simulation environment is described. For this purpose, a powerful simulation system has been used and a flexible security assessment framework developed. The DSA system constructed is user oriented and enables simple evaluation of power system security. The assessment is made in respect to some user defined security constraints considering normal or contingency provoked system operation. For reporting of the results different visualization formats are available. The DSA system is fully automatic and can process any number of study cases without user interaction. It targets high flexibility in power system research and maximum performance at minimum hardware requirements.**

I. INTRODUCTION

DEREGULATION principles and higher economic objectives force the operators to operate power systems closer and closer to their physical limits. Under these conditions, unexpected events easily cause system failures possibly leading to cascading events or even blackouts. In order to withstand these conditions and to ensure reliability of supply, power systems are subject to continuous upgrades and network modernization. As a result, they gain robustness and are well interconnected however are growing in size and complexity. The analysis used to investigate system's performance in the planning stage as well as in its operation is dynamic security assessment (DSA).

The DSA is considered as essential tool in investigation of a degree of risk in power system's ability to survive imminent disturbances (contingencies) [1]. It can be made using various methods, differing in computational complexity. The most complex are the deterministic methods using analytical solutions (time-domain numerical integration) whereas the simplest approach is the direct inference from measurements of power system quantities. In between there are hybrid approaches combining simulation with some direct or measurement-based method [2].

The time domain DSA is a multi task operation. It requires definition of power system security indices used to provide a relative measure of severity in the transient condition, development and application of contingency screening and ranking methods, application of simulation tools, and advanced visualization (Fig. 1).

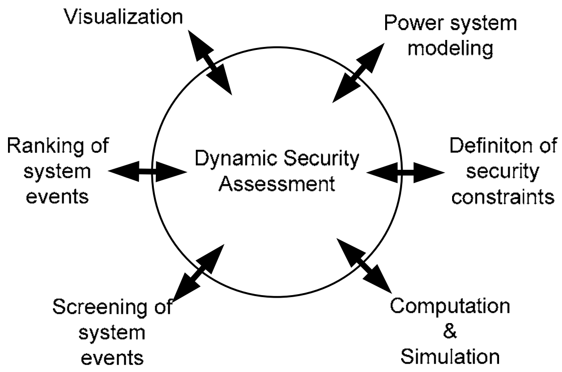

Figure 1 Components of DSA

The security indices in DSA capture the dynamic state of the power system after fault clearance. Each aspect of power system security can be represented by its own index [3] nevertheless also methods for a single all-encompassing security index are available [4-5]. Reliable indices are important for successful contingency screening and ranking. The screening methods classify contingencies into secure and insecure cases, whereas the ranking methods rank their severity.

Moreover, simulation in time domain is known for its computational burden. Although modern processors have bridged the gap between the available computing power and expectations, the online application is still challenging. Common approach to enhance the computational efficiency is to use parallel processing and criteria for early termination of the simulation.

In this paper, implementation of DSA concept into real time simulation environment is described. For the purpose, a powerful simulation system has been used and a flexible security assessment framework has been developed. DSA application constructed targets high flexibility in investigation of power system operation scenarios and maximum performance at minimum hardware requirements.

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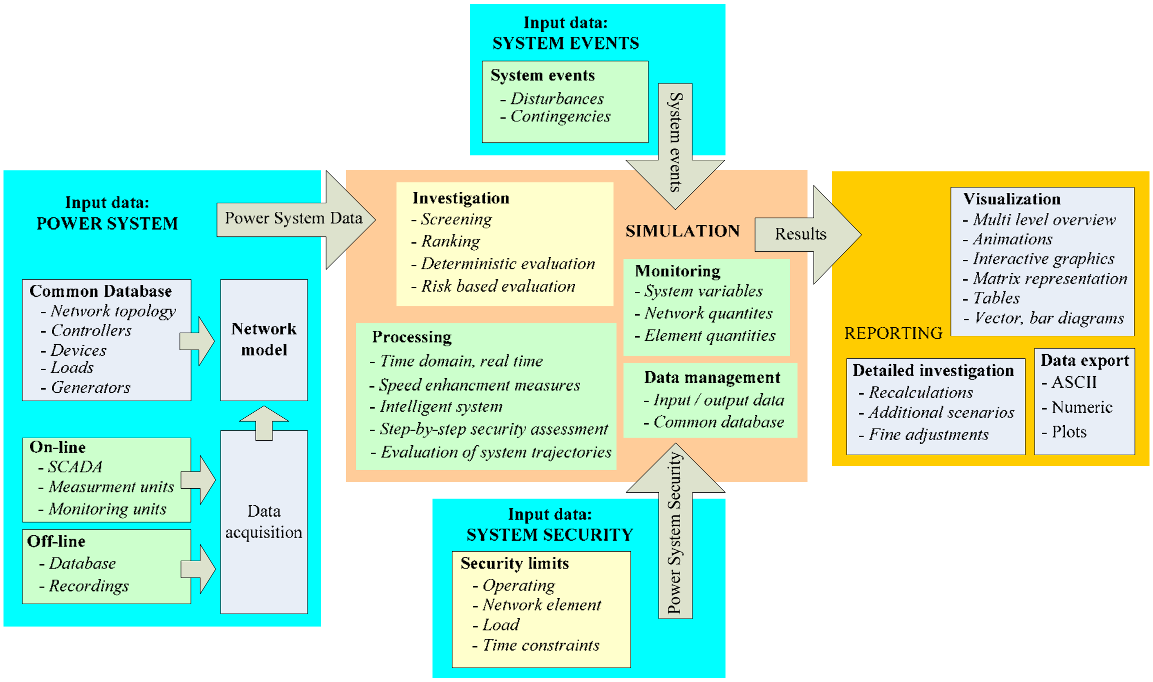

Figure 2 Components of DSA

II. STRUCTURE OF A DSA SYSTEM

To accurately assess the security of a power system a flexible and modern assessment framework is essential. It should aim to perform analysis in real time and provide reliable results. Elements of such a framework can be grouped into the main components illustrated in Fig. 2.

The accuracy of a DSA system is strongly related to the quality of input data. Important are detailed representation of a power system and a credible snapshot of the system's condition.

A system has to be operated in accordance with the system load constraints, operational constraints and 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/over voltages, critical loading of lines, critical under/over frequencies 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.Full functionality of a DSA system is achieved by application of visualization functions. Modern design tools offer unlimited options nevertheless security assessment results should be displayed in simple and meaningful manner. Prime way is to use multilevel structure, different display formats, and to highlight crucial information.

A flexible DSA calculation process is shown in Fig. 3, 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, over current, under-/over frequency, stability, damping etc. These criteria can be combined individually to define a suitable set of criteria to describe the constraints of the system.

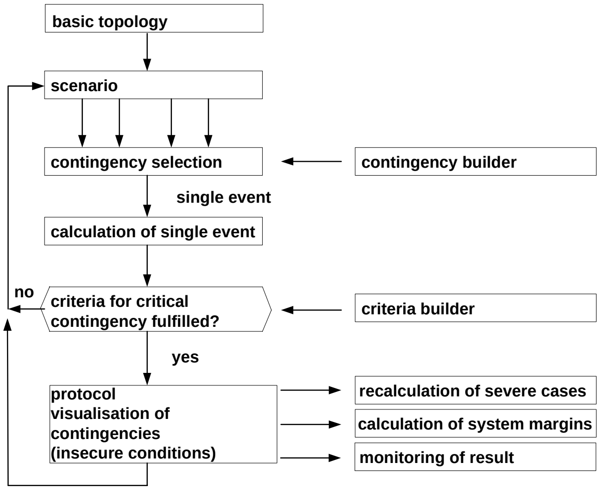

Figure 3 Structure of the DSA system

III. SOFTWARE IMPLEMENTATION

Simulation system used for implementation of the DSA is PSS™NETOMAC [6]. The simulation system provides open environment for user interaction and enables simple implementation and management of DSA tasks.

Fig. 4 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 (under voltage, over current, etc.) or by network elements (generator, line, etc.).

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

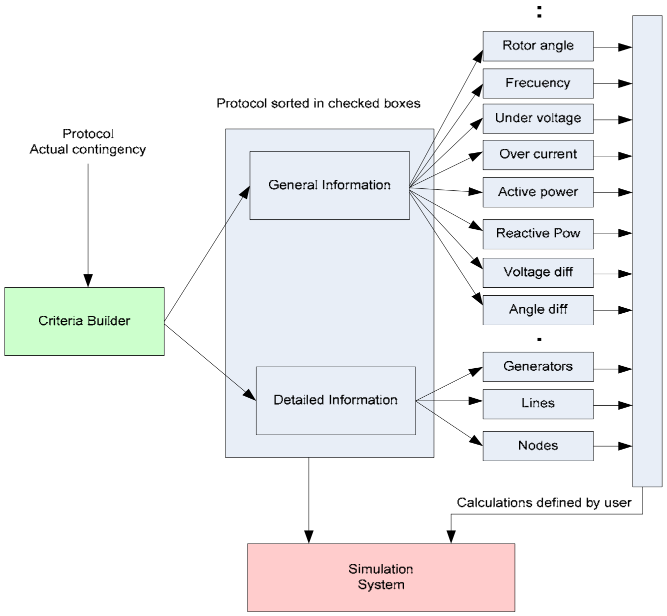

Figure 4 Re-calculation part of criteria builder – secondary tasks

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.). Also re-calculation of the cases is possible.

The contingency screening process is implemented by Boolean algorithms. In processing, power system state variables are searched for violations of limits representing the security criteria and if any are determined, Boolean variables adopt a binary TRUE (insecure) or in the opposite case a binary FALSE (secure). In final, each security issue is represented by a binary record, adequate for direct security assessment or for construction of security indices. An example of criteria and indices for contingency screening and ranking is given in the following chapter.

A. Contingency Screening and Ranking

The dynamic behaviour of power systems is known as complex and difficult to classify. The problem is especially apparent in the area of defining security measures for screening and ranking of contingencies. In screening, contingencies are classified as secure or insecure, whereas in ranking they are ranked considering their severity. The screening and ranking can be done using traditional deterministic approach or risk-based approach.

In the deterministic approach, security limits are expressed in form of inequality constraints providing admissible limits of system quantities. The implemented constraints are as follows.

Bus voltages are constrained by (1)

$$V_{j\,\min} \le V_j \le V_{j\,\max} \tag{1}$$

$$j = 1, \ldots, n$$

where j is the investigated system bus and n the number of system buses. The boundaries are a time variable in order to assure satisfactory voltage transient with regards to angle/voltage stability system requirements. Moreover, maximum voltage difference between two neighbouring nodes is constrained by (2), where V_i and V_j are the node voltages and ΔV_{ij} is the maximum admissible voltage difference.

$$V_i - V_j \le \Delta V_{ij\,\max} \tag{2}$$

Thermal overloading of network components is limited by (3)

$$k = 1, \ldots., m$$

$$I_k \le I_{k\,\max} \tag{3}$$

where I_k is the current carried by the k-th component, $I_{k\,\max}$ is the thermal rating of the same component and m is the number of components. The boundary can be a time variable if short overloading of components is acceptable. Frequency deviation in network buses is constrained by (4), where f_k is the bus frequency, f_0 is the rating frequency and Δf_{kmax} is the maximum admissible deviation.

$$j = 1, \ldots., m$$

$$\left| f_j - f_0 \right| \le \Delta f_{k\,\max} \tag{4}$$

Control variables are subject to the inequality constraints formulated by (5), (6) and (7). P_{Gk} and Q_{Gk} are the active and reactive power produced and V_{Gk} the voltage established by the k-th generation unit. In addition, rotor angles of generators should not exceed the limits given by (8).

$$k = 1, \ldots., z$$

$$P_{Gk\,\min} \le P_{Gk} \le P_{Gk\,\max} \tag{5}$$

$$Q_{Gk\,\min} \le Q_{Gk} \le Q_{Gk\,\max} \tag{6}$$

$$V_{Gk\,\min} \le V_{Gk} \le V_{Gk\,\max} \tag{7}$$

$$\delta_{Gk\,\min} \le \delta_{Gk} \le \delta_{Gk\,\max} \tag{8}$$

In addition to the direct criteria also derived criteria capturing the change in the system state variables can be used. The criteria can be based on:

- change of rotor angle differences
- change of rotor angle differences with respect to centre of inertia
- change of voltage and currents
- change of generator speed or system frequency

- change of transient energy of generators
- acceleration of generators
- system oscillation and damping

There are several indices which have been established in the DSA to capture the fluctuations in the system state variables. In literature various definitions are given. Nevertheless, for time domain implementation the ones with analytical background are most convenient [5], [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 (11).

$$dot1 = \sum_{i=1}^{NG} f_i \cdot \omega_i \tag{9}$$

$$fi = P_{mi} - P_{ei} - \frac{M_i}{M_t} \cdot P_{COI} \tag{10}$$

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

$$P_{COI} = \sum_{i=1}^{NG} (P_{mi} - P_{ei}) \tag{11}$$

where:

M_i: inertia constant of each generator

M_t: total inertia constant of all generators

P_{mi}: mechanical power input of each generator

P_{ei}: 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 (12, 13).

$$dot2 = \sum_{i=1}^{NG} f_i \cdot \Theta_i \tag{12}$$

$$dot3 = \sum_{i=1}^{NG} \omega_i \cdot \left(\Theta_i - \Theta_i^{cl}\right) \tag{13}$$

where:

Θ_i: rotor angles with respect to COI

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

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 (14). Namely, the relays, protecting the generator against asynchronous operation, are adjusted is such a way that the load angle of the generator (δ_i) does not exceed a certain value (e.g. 120°).

$$AI = \min\left\{1,\ \max_{i=1,\dots NG}\left(\frac{\delta_{ci,\max}}{\delta_{c,\max,adm}}\right)\right\} \tag{14}$$

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 $\Delta f_{i,\max,adm}$ (15). 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.

$$MFDI = \min\left\{1,\ \max_{i=1,\dots NG}\left[\frac{\left|\Delta f_{i,\max}\right|}{f_{\max,adm}}\right]\right\} \tag{15}$$

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 (16) 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.

$$TFDI = \min\left\{1,\ \max_{i=1,\dots NG}\left[\frac{\int_0^{ts}\left|\Delta f_i(t)\right|dt}{\Delta f_{\max,adm}ts}\right]\right\} \tag{16}$$

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 (17), 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.

$$DVI = \min\left\{1,\ \max_{i=1,\dots N}\left[\frac{V_n - v_{i,\min}}{V_n - v_{i,\min,adm}}\right]\right\} \tag{17}$$

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 $\Delta vi,lim$, where the latter is the percentage of the rated voltage.

$$QSVI = \min\left\{1, \max_{i=1,\ldots N}\left[\frac{\Delta v_{i,aft}}{\Delta v_{i,\lim}}\right]\right\} \qquad (18)$$

7) *Power Flow Index (PFI)*

The index takes into account the post-fault power flow since its excess may activate the line protection. The index is defined by (19), 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.

$$PFI = \frac{1}{NL}\sum_{i=1}^{NL}\omega_i\left(\frac{P_{i,aft}}{P_{i,\lim}}\right)^n, \; if \;\; P_{i,aft} < P_{i,\lim} \;\; \forall i \qquad (19)$$

$$PFI = 1, \; if \;\; \exists \;\; P_{i,aft} \geq P_{i,\lim}$$

8) *Load Shedding Index (LSI)*

The LSI (20) 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.

$$LSI = \frac{P_{shed}}{P_{total}} \qquad (20)$$

B. *Visualization and Monitoring*

Clear graphical representation of power system security is essential in recognizing weakest points of a system. Therefore, DSA must include meaningful visualization of information characterizing important security issues. Considered DSA system provides various output formats to meet these requirements, including interactive graphics, animations, matrix representation, electrical diagrams, tables, etc. as shown in Fig. 5.

1) *Interactive graphic, Recalculations and Animations*

Interactive graphic provides plots of system quantities with time reference and enables output format manipulations. User selected plots can be easily scaled by pre- or user-defined mathematical expressions and analyzed by application of Fourier analysis. Moreover, each plot can be investigated in detail by zooming in the time scope and using on-line cursor control.

If a security violation is reported, recalculation of conditions leading to this violation is possible. By definition of additional scenarios more exact security limits can be determined. Moreover, system transients can be investigated using bar or vector animations of network quantities in respect to a selected criteria. Animations are available for simulation time set and are controlled through traditional control panel (play, pause, stop).

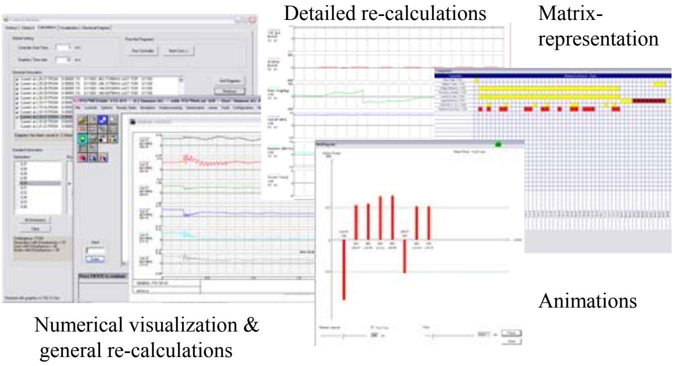

Figure 5 Visualization and monitoring of the dynamic behaviour of power systems in case of system contingencies

2) *Matrix representation*

Common approach in providing of security assessment results is to use summary tables. These tables comprise a list of investigated contingencies and information regarding security violations. Matrix representation extends the visualization frame of such summary tables by sorting the system events by applied contingency and related network element, assessment criteria, and by organizing them in reference to a colour scale. Moreover, the matrix comprises hyperlinks enabling direct access to an event associated graphics.

3) *Other formats*

In addition, other formats, such as for electrical representation of a power system or for table representation of security assessment associated data, are available. These formats can be adjusted to meet user requirements and enable multi-level overview of DSA results. In addition, also a landscape- based format is also available (Fig. 6)

Figure 6 System visualization in reference to the landscape

C. Study case

The European UCTE system has been used to demonstrate the performance of the DSA. The system 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 has been built with 610 generators, 4400 nodes, 12000 grid branches, and 1050 controllers. The system model has been validated using measurements of the installed Wide Area Measuring System (WAMS).

Based on the comparison of the simulation results of a 300MW trip in Spain shown in Fig 8 and the recordings of WAMS shown in Fig 7 it can be concluded that the model represents the overall electromechanical system behaviour with sufficient accuracy. The simulation has been performed for 15 seconds under real time conditions. To achieve real time conditions time steps of 10 ms are the limit. However, for the electromechanically behaviour the accuracy with time steps of 20 – 50 ms is also suitable.

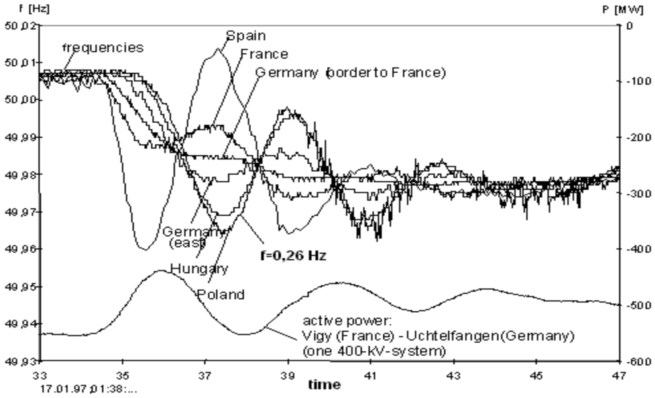

Figure 7. Interarea oscillation after300 MW trip, WAMS recordings

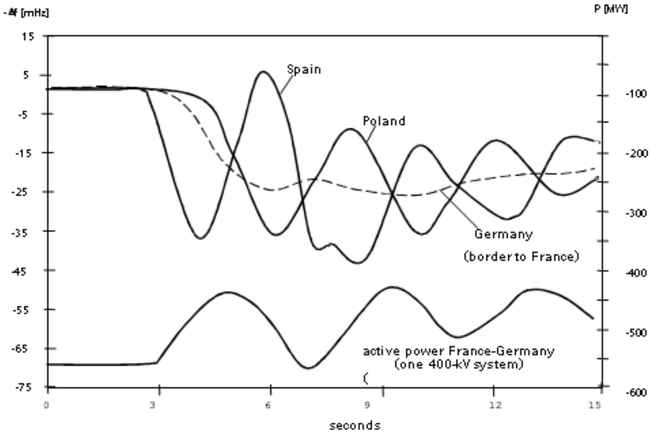

Figure 8. Interarea oscillation after300 MW trip, simulation results

Using the eigenvalue mode of the DSA system the inter-area oscillations of the power system can be easily monitored, moreover the system also shows how and which generators are involved in the oscillation (Fig. 9).

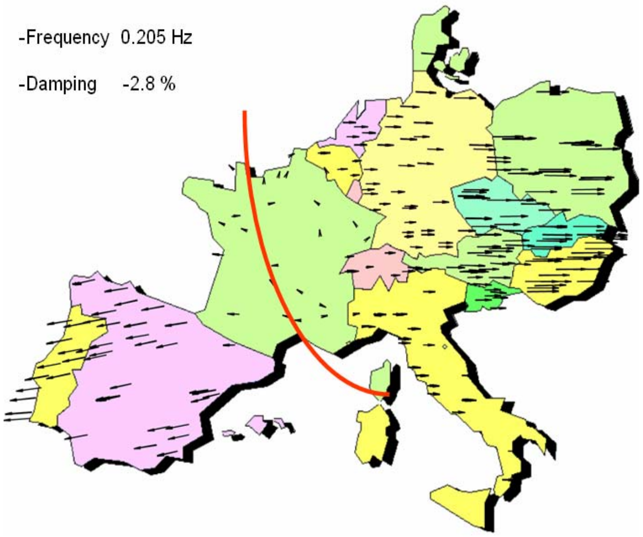

Figure 9 Monitoring of geographical mode shape of an inter-area oscillation in the UCTE system (Spain oscillates against Central Europe and the CENTREL Counties)

Because of the flexible change from time domain to frequency domain calculation remedial actions and preventive measures can be checked very fast. Fig 10 depicts countermeasures at different generators to increase damping in the system, here shown in the time domain, but analyzed in the frequency domain by system eigenvectors and residues.

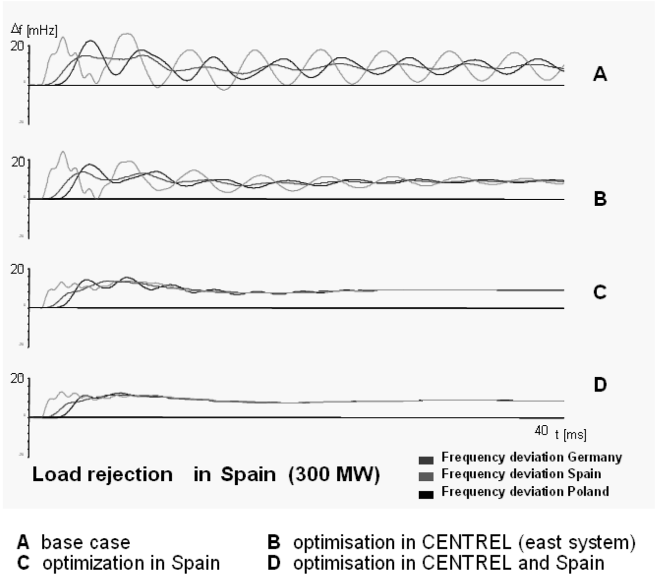

Figure 10 Countermeasures to improve system stability and reduce inter-area oscillation, checked by frequency deviation monitoring in different countries

IV. CONCLUSION

In this paper, a simulation system implementation of a DSA is described. The outcome is user oriented application providing high flexibility in power system research and capable of performing in real time. Using graphical interface options user can define contingencies and construct scenarios, which are in computations considered in respect to user defined security constraints. Severity of contingencies can be investigated using traditional deterministic security assessment or risk-based security assessment. For reporting of DSA results different visualization formats are optional. Moreover, multilevel view is possible. The application has been tested for performance in a case study.

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VI. BIOGRAPHIES

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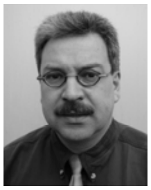
Edwin N. Lerch (1953) received his Dipl.-Ing. degree from the University of Wuppertal/Germany in 1979, where he also completed his PhD (Dr.-Ing.) in electrical engineering in 1984. Since 1985 he has been a member of the systems planning department at Siemens in the industrial power system and machine group. He is currently working in the areas of power system stability, dynamics of multimachine systems, control, optimization and identification problems in electrical power systems. Since 1994 he is director of the department group 'Industrial Systems, Dynamic of Grid and Machine'.



Olaf U. Ruhle (1965) received Dipl.-Ing. and his Ph.D. degree in electrical engineering from the Technical University of Berlin in 1990 and 1994 respectively. Since 1993 he is a member of Power Transmission and Distribution Group and the system planning and consulting department at Siemens in Erlangen, Germany. He is working on power system stability, dynamics of multimachine systems, control, optimization and identification problems in electrical power systems. He is responsible for the NETOMAC program system support, sale and training worldwide.

Rainer Krebs, born 1958 in Germany (member of VDE, CIGRE, IEC and DKE), received his Dipl.-Ing. degree from the University of Erlangen in 1982. From 1983 to 1990 he worked as an assistant professor at the Institute for Electrical Power Supply at the same University. In 1990 he received his Dr.-Eng. degree in Electrical Engineering. 1990 he joined Siemens AG, Power Transmission and Distribution, System Planning Department. Since 1998 he is director of the System-Protection and System-Analysis Tools Department and since 2006 he is 'Principal Expert for Power Technologies'. In parallel he started in 2003 as lecturer at the University of Magdeburg.