21, rue d'Artois, F-75008 Paris
http://www.cigre.org

39-101

Session 2002
© CIGRÉ

ADVANCED PERSPECTIVES AND IMPLEMENTATION OF DYNAMIC SECURITY ASSESSMENT IN THE OPEN MARKET ENVIRONMENT

International Contribution by

A. BIHAIN – Tractebel, Belgium
G. BURT – Strathclyde University UK
F. CASAMATTA – CESI, Italy
T. KORONIDES – HTSO, Greece
R. LOPEZ – Alstom T&D, France
S. MASSUCCO* – University of Genova, Italy
D. RUIZ-VEGA – University of Liege, Belgium
C. VOURNAS – ICCS/NTUA, Greece

Summary *– The paper provides a detailed overview of an on-going industrial-research project supported by the EU and involving a large Consortium of Industries, Research Centers, Universities and System Operators. The preliminary phase for analyzing and defining the requirements of a DSA (Dynamic Security Assessment) tool to be included in the EMS (Energy Management System) environment is reported. The decision process to define the hardware and software architecture adopted for the implementation of a prototype is explained.*

The main features of an advanced DSA tool should allow assessing and improving the network dynamic security into a deregulated market environment. The project development is subdivided into three phases (project requirements and calibration, prototype system development, on-site experimentation) that are reported in the paper. The theoretical bases of the application functions included in the DSA (TSA – Transient Stability Assessment, VSA – Voltage Stability Assessment, TS – Training Simulator and MS – Market Simulator) are described into detail. The final product will be tested on the field at two experimental sites provided by two existing TSOs (Transmission System Operators). The paper also reports the set-up of suitable scenarios for the validation phase of the DSA tool.

Keywords*: Power system security - Dynamic security assessment - Transient stability - Voltage stability - Operator training simulator - Market simulator - Transmission capacity*

OMASES Working Group: Bihain A. (Tractebel, B), Burt G. (University of Strathclyde, UK), Casamatta F. (CESI, at the moment of the study, I), Christoforides G. (HTSO, GR), Cirio D. (University of Genova, I), Fiorina M. (CESI, I), Galloway S. (University of Strathclyde, UK), Giri J. (Alstom T&D, USA), Hassé G. (University of Liege, B), Hatziargyriou N. (National Technical University of Athens, GR), Kabouris Y. (HTSO, GR), Koronides T. (HTSO, GR), Lopez R. (Alstom T&D, F), Manos G. (National Technical University of Athens, GR), Massucco S. (University of Genova, I), Mc Donald J. R. (University of Strathclyde, UK), Morini A. (University of Genova, I), Pavella M. (University of Liege, B), Ruiz-Vega D. (University of Liege, B), Salvetti M. (CESI, I), Signoretty L. (Alstom T&D, F), Siewierski T. (University of Strathclyde, UK), Silvestro F. (University of Genova, I), Stubbe M. (Tractebel, B), Van Cutsem T. (University of Liege, B), Vournas C. (National Technical University of Athens, GR), Wehenkel L. (University of Liege, B).

1. INTRODUCTION

The liberalization of the electricity market, started by the European Directory 92/96 and even before in other countries, has generated the unbundling of large Utilities into separated Generation, Transmission and Distribution Companies with consequent changes in the operating conditions of electric power systems [1], [2]. To achieve the highest economical benefits of the market, the grid has to be operated with maximized power transfers. The necessity of fully exploiting transmission corridors makes transmission facilities one of the major concerns of the whole system. Apart from the obvious physical constraints like over-currents on transmission facilities, system-wide dynamic limits, such as Transient Stability (TS) and Voltage Stability (VS), have acquired more and more importance. An unstable behavior may lead to an extended outage, partial black-out or even a complete black-out, thus severely jeopardizing system security. Furthermore, maximizing transmission power flows will allow reducing the expansion of transmission systems that is an important aid to front environmental constraints on future system development particularly if the overall system reliability must be kept at high levels.

In this context EMS (Energy Management System) operators responsible for system security will need several synthetic information about system conditions [3]. On-line information in terms of indices for TS and

---

* Corresponding author's address: Electrical Engineering Dept. – University of Genova, via Opera Pia 11a, 16145 Genova, Italy

VS, for Available Transmission Capacity (ATC) and others, are expected to provide guidelines for assessing and maintaining system security, for implementing remedial actions based on predictive control or even for activating real-time corrective controls [4].

The paper provides a detailed overview of an on-going industrial-research project supported by the EU and involving a large Consortium of Industries, Research Centers, Universities and Electrical Utilities [5]. The preliminary phase for analyzing and defining the requirements for a DSA (Dynamic Security Assessment) tool to be included in the EMS environment are reported in the next sections together with the theoretical supports for the developed methodologies and the overall architecture that have been guiding the realization of a prototype.

The features of such an advanced DSA tool currently under development will allow assessing and improving the network dynamic security into a deregulated market environment in accordance with the most updated needs [6], [7].

2. SYSTEM REQUIREMENTS AND ARCHITECTURE FOR ADVANCED DSA

2.1 Generalities

Although generation is the sector most directly influenced by competition, it is clear that only a secure and efficient transmission system can allow the generation market to exist. The High Voltage (HV) European Electrical Transmission System interconnecting the European Countries amounts to about 200,000 km of 220 kV and 400 kV transmission lines. The consequent level of complexity related to the control of such a large system in a secure manner can be easily recognized.

Security is defined as the capability of guaranteeing the continuous operation of a power system under normal operation even following some significant perturbations. As security is a major if not ultimate goal of power system operation and control, the new scenario imposed by power system industry is particularly stressing the necessity for a fast and reliable security assessment. In the past, static security assessment (SSA) based on intensive load-flow calculations had been sufficient in ensuring good system operation. Nowadays, in the liberalized market, the operation of Energy Management System (EMS), which is designated to improve network security and reliability, is under the responsibility of the Independent System Operator (ISO), an entity not owing generation and, quite often, not even transmission facilities, which must be able to monitor and control the power system. These considerations stress the concept that the present situation dramatically requires dynamic security assessment (DSA) to be extensively performed within EMS.

DSA can deal with transient stability problems and/or voltage stability problems that respectively require transient stability assessment (TSA) and voltage stability assessment (VSA). DSA tools that have been developed in the recent past are now on the way to be integrated into EMS [5], [8], [9], [10], [11].

DSA is strongly related to: the examination of large quantity of data, the use of past operating experience, the capacity of rapid decision based on both qualitative and quantitative information. When dealing with DSA a very large number of contingencies should be considered so that a huge contingency screening must be performed. Moreover in order to add some value to the simple “assessment phase”, the DSA tool is expected to suggest both preventive and remedial actions in order to lead the power system to a more secure state or to avoid its degradation into an insecure or an emergency state [10], [11], [12].

To the same extent, EMS operators must be duly informed of and trained on the detrimental dynamics of the power system leading to major incidents. The training simulator modeling capability must be extended in order to reproduce in real time fast and slow phenomena with unstable behaviors [3], [13], [14].

2.2 An advanced DSA project: OMASES

A EU partially funded project named OMASES [4] (**O**pen **M**arket **A**ccess and **SE**curity assessment **S**ystem) started in 2001. The involved partners and individuals are mentioned in the OMASES Working Group list. The project is a 2.5 years research activity within the aim of the Framework V Energy call. In the context of this large research theme, the OMASES goals are:

- To provide a transparent methodology to assess the network dynamic stability, the need for topology change, generation rescheduling, or load shedding
- To increase the power flow on electrical lines by computing dynamically operating limits
- To reduce the lines incidents resulting from stability problems by simulating dynamic contingencies
- To improve the generation allocation by computing the unit commitment in accordance with the dynamic limits and the electrical market demand
- To adjust emergency protection to more accurate values either off line or on line (according to field equipment capabilities) by providing engineering study tools able to reproduce adequately the dynamic behaviour of the power system
- To provide advanced real time dynamic simulation tool for operator training
- To improve the quality of life by helping in the meeting of ecological objectives that are a direct result of previous goals since the need for new electrical lines and new generating plant may be reduced.

The OMASES overall structure includes different tools for Transient Stability Assessment (TSA), Voltage Stability Assessment (VSA), Training Simulator (TS) for operators, and Electrical Energy Market Simulator (MS). An outline of the DSA framework adopted for OMASES, as well as the interactions among the different tools is described in the next section.

OMASES is intended to be inserted in existing EMS or to be engineered in new EMS structure. The DSA tool will be potentially used in the following modes: (1) Engineering mode, (2) Real-time mode, (3) Training mode. A short description of each mode is reported below.

- **Engineering mode:** it is the off-line application of TSA and VSA studies involving or not the market environment and performed mainly for planning purposes. There is not particular urgency on the time response, as the results are not needed for operation.
- **Real-time mode** is the use of a DSA tool for Energy Management System operators. The tool is effectively used during system operation to provide alarms related with the dynamic security of the power system.
- **Training mode** is the use of a DSA tool for training EMS operators. In this case, the EMS and the power system itself are replaced by a simulation engine and a Human Machine Interface (HMI). The operator gets used with the DSA tools and power system dynamics, performs analysis (future scenarios, post-event analysis, etc.) of the existing electrical system and/or experiments. In this mode, market rules can be used to realistically affect on the operational stage.

The results coming from OMASES security analysis tools (on the following referred to as DSA Analytical Functions TSA and VSA) will be available on OMASES HMI. There are significant differences in the requirements for the above modes, particularly for time responses and HMI. Engineering mode does not pose too stringent requirements whereas real-time and training modes do.

Also the role of electrical energy market is under discussion for DSA tools. Market structures are still evolving and under revision. The UK market for instance has recently passed from a day ahead bidding to a structure for which bidding is accepted until 3.5 hours before real operation (NETA system). In any case, there is a time de-coupling between the analysis required by DSA and the analysis of MS and TS. Therefore, within OMASES, the MS is intended to provide credible scenarios for successive evaluation of DSA. The role of MS is also important in providing effective and "real-life" situations in the TS environment for operator training. Thus the TS and the MS will be used both for the Engineering Mode and for the Training Mode.

The MS is used to identify feasible and credible scenarios for which the DSA has to be investigated within the usual EMS cycle or at the occurrence of some variations identified by the SCADA system. According to what above stated the TSA and VSA tools (which constitute the core of the DSA analysis) can be viewed as sort of subroutines to be called by an external procedure that simulates the market and the operator environment.

The interactions between the MS, the TS and the DSA are "open-loop" actions. A feedback from the DSA to the operator can be used for validating the market strategies by evidencing possible transmission congestion and suggesting guidelines for their solutions.

2.3 OMASES architecture

In this context, the EMS is essentially seen as real-time network data provider to feed the Analytical Functions (AF) which conduct the dynamic stability analysis and market simulation. These advanced functions will allow the EMS operators to improve the operating conditions of the power system. Because some of these functions will run continuously in a pseudo real-time mode, they will be able to detect critical situations and warn the operators against potential risks. Detailed results from the AFs will also be available to the operators to further investigate detected problems and to implement recommended corrections.

The proposed software architecture is based on a multi-tier, distributed architecture which provides a loose-coupling integration with the EMS, while allowing a tighter integration with the AFs. The communication infrastructure is based on Message-Oriented-Middleware (MOM) services and the centralized data repository relies on a relational database management system that provides room to AFs for storing shared and private data.

The global frame that will constitute the DSA environment is shown in figure 1 and mainly consists of:

- An existing EMS environment to which OMASES will be connected in a way that allows file sharing for communication.
- A data server which will host any shared information, database systems, message systems, etc.
- One or more systems to be used by operation personnel hosting user interface processes.
- One or more systems hosting computational processes.
- A LAN for inter-machine communications.

A principal goal of the OMASES architecture is to minimise the amount of changes that are required to the existing EMS systems thus allowing a sort of plug-in of the tool in existing EMS.

The OMASES applications run in a distributed environment, with a link to its host EMS over which a real-time picture of the power network is obtained. OMASES itself consists of computation hosts, a server host, and a number of User Interface (UI) hosts.

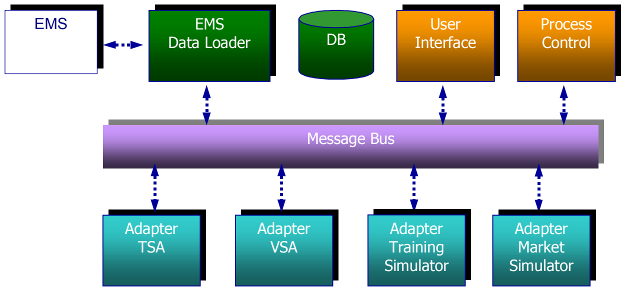

Figure 1 – Overall EMS-OMASES Architecture

There will essentially be two ways to use the OMASES system:

- A first way, where the OMASES system is coupled to an EMS system. In this configuration, the EMS feeds OMASES with network solutions and the execution of the Dynamic Stability Analysis (DSA) functions is periodic and synchronised with the data transfer from the EMS. Although the time period for the DSA execution is in the range of 15 minutes, this mode is referred to as the real-time mode in this paper.
- A second way, where the OMASES system may be coupled or not to an EMS system. In this configuration, the execution of the Dynamic Stability Analysis (DSA) functions and/or simulation functions such as Training Simulator (TS) and Market Simulator (MS), is launched manually by the user. This mode is referred to as the study mode in this paper.

Any number of additional machines could be configured to support the computational workload of the AFs (i.e.: TSA, VSA, MS, TS). The system can also be configured to support multiple instances of a given application, each instance having its own environment. The idea of having several parallel boxes for the same task to enhance response times seems particularly suitable for TSA. For instance, several boxes TSA_1, TSA_2, …, TSA_n could be used in parallel. Parallel operation for the VSA package seems less essential but should be made available if required.

One of the main objectives of the OMASES project is to allow for different software functions to interact with an Energy Management System (EMS). OMASES functions are based on existing or current applications developed by Consortium Members. As such, these functions presently have their own, proprietary data models. OMASES needs to provide a common model to facilitate data exchange. Main data flows and modeling principles for the OMASES are:

- Network state – Real-time or study network state coming from the EMS
- Planning data – System load forecast and generation schedules
- Dynamics – Dynamic models of power plants and protection devices
- Contingencies – Set of events for which stability assessment is to be made
- Stress scenarios – Load stress scenarios (load zones, transfer directions etc.)
- Public results – Dynamic stability assessment results to be presented to OMASES users

OMASES data will be stored in a relational database. The data sets identified above consists of one or several database tables. EMS interaction with the OMASES platform is based upon EMS exporting flat ASCII files towards the OMASES environment. These files contain either periodic real-time network states created by the State Estimator or study situations from a Power Flow application. Any EMS capable of exporting a file in the specified format shall be able to easily integrate with the OMASES platform.

3. APPLICATIONS WITHIN THE DSA ENVIRONMENT

3.1 Overview of the Application Functions within OMASES

The core of the OMASES project is based on existing application software or will lead to the development of new ones that will cover the new and advanced aspects of power system operation. These applications are related to:

- *economic aspects*: a Market Simulator (MS) will define realistic generation patterns taking into account the various actors of the energy market
- *real time security functions*: a Voltage Stability Assessment (VSA) function is based on the so-called Quasi-Steady-State approach, mostly suitable for long-term voltage stability studies. A Transient Stability Assessment (TSA) function makes use of full transient stability simulations
- *operator training: an advanced real time training Simulator (TS) will be set up and used also for validation*

For both TSA and VSA tools, analysis will consist of calculating system security indices and margins for a set of contingencies applied on a real time scenario taken from the EMS or from the TS.

Such advanced techniques require validation as well as a good understanding of the results. Thus an advanced real time simulator with detailed physical models of the power system is the adequate tool for facilitating the tuning and testing of VSA and TSA applications. The Training Simulator (TS) will also be suitable for teaching and training engineers and operators to system operation in normal and abnormal conditions.

3.2 The Individual Analytical Functions

3.2.1 TSA – Transient Stability Assessment

A synthetic overview of the TSA and Control (TSA&C) function is reported in figure 2.

The theoretical background and the current state of TSA&C make use of the SIME method, a tool that has been developed at the University of Liege [4], [10]. SIME is a hybrid transient stability method. The great advantage of hybrid over direct methods, in general, [15] is their capability of using detailed models of power system equipment and controls available in the most advanced time domain simulation programs [13], [14].

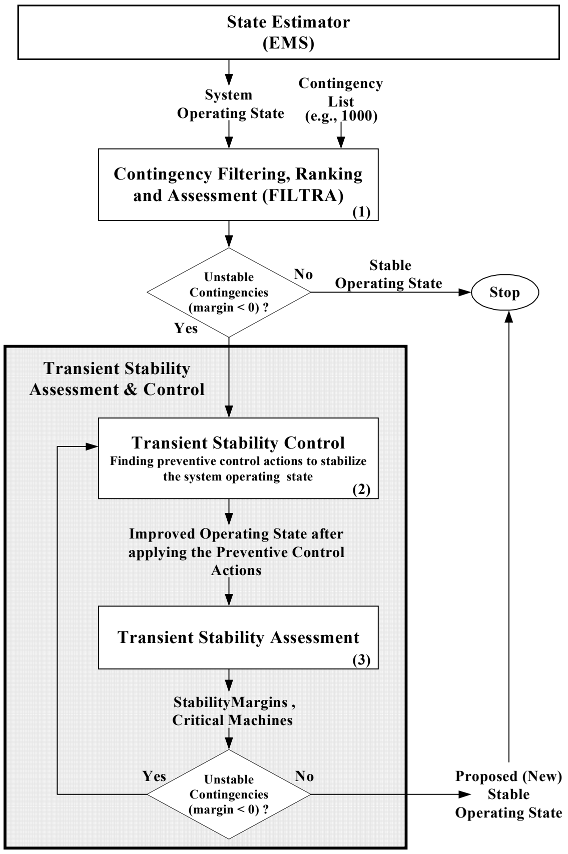

Fig. 2 – An integrated On-line Filtering Ranking Assessment and Control scheme

The particular SIME method transforms the trajectories of a multi-machine power system provided by a time-domain program into the trajectory of a One-Machine Infinite Bus (OMIB) equivalent**.** Let us mention that SIME has been coupled with several time domain programs [4]; within OMASES, the power system simulation engine is provided by EUROSTAG [13].

SIME refreshes the OMIB parameters at each time step of the time-domain (T-D) program, so as to provide an accurate replica of the transient stability assessment of this latter. The following are further information on SIME features and operation.

Computation of stability limits. The search of stability limits (critical clearing times (CCTs) or power limits) generally relies on the computation of margins and their pair-wise extrapolation. The search is iterative and proceeds from "right to left", by simulating successive unstable cases of decreasing severity, assessed by their negative margin. The simulations stop as soon as a stable case is met.

Contingency filtering. SIME has the important capability of detecting both first swing and multi swing instabilities. Details on methodology and applications on large-scale power systems are illustrated in [4].

The contingency Filtering, Ranking and Assessment (FILTRA) function is one of SIME's by-products, and is schematically represented in figure 3 [16]. The approximate search of a first-swing stability limit generally requires only two unstable simulations. Thus, given a clearing time, the contingency will be: either first swing stable or first swing unstable. In the latter case, a more refined classification into multi-swing harmless, potentially harmful or harmful contingency may be obtained, using a second simulation with a smaller clearing time.

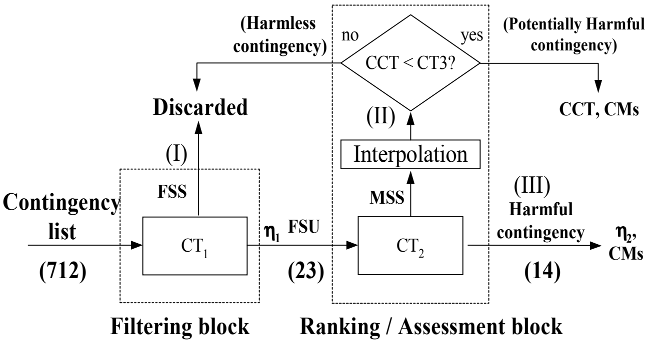

Fig. 3 – A general Filtering Ranking and Assessment (FILTRA) scheme [16]

In figure 3, the numbers within brackets correspond to the number of contingencies of the various classes, for a stability exploration of the Brazilian system (full contingency list amounting to 712).

Transient stability control. By definition, a contingency, which provides a negative margin is unstable. In principle, stabilizing it is equivalent to canceling out its negative margin. In turn, increasing the margin to zero may be obtained by acting on the OMIB mechanical power. By using the equal-area criterion (EAC), this provides a first guess of the total generation power to be shifted from critical machines (CMs) to non-critical machines (NMs). The corresponding rescheduling of NMs, which generally are more numerous, may be conducted so as to comply with additional objectives. The accurate stabilization of a contingency uses this guess to start an iterative procedure similar to that of a stability limit computation. The TSA&C function is a combination of SIME's by-products, and comprises the following steps, as highlighted in figure 2: (1) the output of the state estimator provides the data for performing a Load Flow (LF) study in order to set up a power system state; (2) the dynamic security of this operating state is assessed with respect to a given list of possible contingencies by the integrated TSAC scheme. This scheme is mainly composed of FILTRA (block 1) and the composite block comprising blocks 2 and 3.

FILTRA identifies the harmful contingencies from the generally very large initial contingency list. Most of the contingencies are thus discarded, and the remaining harmful ones are sent to the TSA&C block (block 2 in figure 2), with the information provided by FILTRA for each one of them: critical machines, and margins.

Using this information, the transient stability control block: (a) determines the corresponding control actions (the active power change in each critical machine) for each one of the harmful contingencies; (b) combines the resulting control actions to compute the amount of active power change in each critical machine necessary to stabilize the set of harmful contingencies simultaneously.

For each one of the harmful contingencies, the security of the new operating state is assessed by the TSA block (block 3 in figure 2). If the power system is stable for all contingencies, the new operating state is declared to be stable and the process stops. The overall cycle is repeated until stabilizing all harmful contingencies.

SIME may be used in all three typical application contexts defined for OMASES, namely:

- Expansion planning; for screening contingencies and for sensitivity analysis purposes (placement of a FACTS and exploration of the way it damps inter-area oscillations)
- Operation planning; for congestion management problems and for ATC calculations
- Real-time operation; in a horizon of 30 minutes ahead, i.e. in the preventive mode, for scanning a set of plausible contingencies, identifying the harmful ones and assessing their severity; further, for proposing to the operator remedial actions able to stabilize situations which would arise if any of these contingencies would occur.

Also, the software can be used in order to compute transient stability-constrained maximum allowable power transfer in a set of tie lines. The use of SIME within OMASES is limited to its preventive capability as the DSA is here intended to operate as a support system to aid operator’s decisions. Thus, the following is a list of the capabilities offered by the *PREVENTIVE SIME* within the DSA tool realized within OMASES:

- Calculation of transient stability margins relative to a given contingency.
- Identification of the critical machines relative to a contingency.
- Computation of transient stability limits: critical clearing times or power limits.
- Filtering of contingencies, ranking of potentially harmful contingencies and assessing harmful contingencies: FILTRA software.
- Integrated transient stability assessment and control (TSA&C) software, aiming at the stabilization of harmful contingencies.

Further advanced features are available and are more related to real-time implementation of SIME [4].

3.2.2 VSA – Voltage Stability Assessment

Voltage dynamics in a power system span a range of time scales from a fraction of a second up to tens of minutes. Most of the components and devices constituting a power system play their part in voltage instability/collapse phenomena. Due to its complexity, voltage stability has been classified into short-term and long-term, according to the time frame involved. The general description of power system incorporates the representation of instantaneous dynamics (represented by algebraic constraints), short-term and long-term dynamics [11].

The scope of the VSA part of the OMASES project is to integrate software tools for the assessment of Voltage Security into the DSA package of the OMASES platform. This includes, among others, the analysis of the impact of significant contingencies and the determination of secure operation limits in terms of power transfers in critical corridors or power consumption in load areas. The contingencies to be considered in VSA are:

- the loss of transmission equipment
- the loss of generation equipment
- the loss of reactive compensation equipment
- combinations of the above events.

To meet the real-time requirements, system analysis is based on the Quasi Steady State (QSS) approach for fast nonlinear simulation, together with linearization-based tools for diagnosis [11]. The essence of the QSS approximation is that faster phenomena are represented by their equilibrium conditions instead of their full dynamic representation. This greatly reduces the complexity of the resulting model with obvious benefits in terms of computer implementation, simulation time, and data requirements. This is particularly needed for Voltage Security Assessment in real time. In long-term voltage stability studies in particular, the analysis concentrates on slowly varying components. Thus all short-term dynamics are considered as if at equilibrium; the long-term dynamics are described either by differential equations or discrete time equations.

In most practical situations, there is a good time scale separation between short-term and long-term power system dynamics (tens of seconds versus fractions of a second), which guarantees a close approximation of the long-term dynamics by the QSS model. This has been thoroughly validated in the past [11].

Validation can successively be made off-line by detailed full-scale simulation, which is not fast enough for the real-time applications targeted in OMASES.

The VSA function of OMASES will consist of two modules:

(1) The Voltage Security Analysis Package (VSAP) that aims at providing the operator with security margins with respect to voltage instability. More precisely the objectives of VSAP are:

- to evaluate the impact of contingencies on the voltage behavior of the system
- to compute secure operation limits for given "directions" of system stress
- to display the area(s) in trouble (involved network elements, loads, etc.), for each contingency having a low limit
- to provide an estimate of the time between the disturbance occurrence and the violation of specified operating criteria
- to suggest preventive actions to maintain/increase security margins.

One of the main task of VSAP is the determination of Secure Operation Limits (SOLs) [17]. A SOL refers to some *pre-contingency* stress of the system. A stress corresponds to changes in load and generation, which make the system weaker by increasing power transfer over relatively long distances and/or by drawing on reactive power reserves. This may correspond either to a load increase in an area A_1 covered by generation in a remote area A_2 or to a generation decrease in area A_1 covered by a generation increase in a remote area A_2.

For a given direction of stress, the SOL corresponds to the most stressed operating point such that the system can withstand any contingency out of a specified list. The *default stress direction* is defined by load prediction in each area with participation factors for each generator provided by the EMS AGC.

The default contingencies are all single ones (loss of line, transformer, generator) to which a specified list of double (N-2) contingencies can be added. *Contingency filtering* is an important preliminary step for VSA. Its objective is to identify harmless contingencies, to be discarded from the security limit determination. To this purpose, contingencies are analysed at the maximum stress of interest with a properly tuned post-contingency power flow. Only those contingencies declared potentially harmful are kept in order to be analysed with QSS time simulation [17].

Beside security limits, it may be of interest to analyse *the instability extent* (local vs. global weak area). Such information can be obtained from a snapshot of the system in the marginally unstable case.

Finally, when a security margin is deemed too small, the appropriate preventive counter-measures can be determined. Pre-contingency load shedding or generation rescheduling can be effective ways of restoring a security level.

Thermal overloads can be also incorporated in the analysis, thereby providing a unified treatment of voltage and thermal problems. Security limits then relate to the most constraining between the two aspects.

(2) In-Depth Case Analysis Package (IDCAP) whose aim is to analyze in detail particular Voltage Stability scenarios, such as the system response to contingencies and load increase starting from the current operating point of the system, or from an operating point retrieved from EMS historical data.

The default mode is for IDCAP to run the most constraining contingency provided by VSAP and produce curves showing voltages versus regional load power for the affected region(s). Namely, IDCAP will simulate the effect of the critical contingency starting from the current operating condition (no pre-contingency stress) and assuming a post-contingency stress pattern. IDCAP will produce the PV curve(s) showing the voltages at representative buses as a function of the total load of the affected region(s).

The IDCAP module deals with several aspects of *post-contingency* analysis. It operates as follows.

Long–term simulation starts from a solved load flow retrieved from the EMS (current state estimation, or a saved case), a given contingency (default is the constraining one calculated by VSAP), and a direction of system stress. The simulation is performed using the QSS approximation. The user can easily apply additional disturbances to the default scenario, or simulate an altogether different one, by specifying disturbances such as: load changes (increase/decrease, by node, area or for the whole system), generator ramp and/or set-point adjustment, branch tripping and/or reclosing, generator outage, load switching (for each independent load component, i.e. constant power load, constant impedance load, exponential load, induction machine) and load pick-up (uniform ramp of all load components).

In addition, the IDCAP module can perform the following tasks:

- *Long-term instability monitoring*: performed during the simulation, in order to determine the critical point, where long-term voltage stability is lost
- *Short-term instability analysis*: to identify the system components responsible for a loss of short-term equilibrium point, when such an event is met. After this point, an extended QSS method is available for the continuation of the simulation
- *Evaluation of post-contingency countermeasures* such as tap-blocking, load shedding, tap adjustment, capacitor switching, etc. to avoid or mitigate voltage instability

- *Post-contingency loadability limits*: evaluated for specific areas and are plotted in the form of regional PV curves.

The overall structure of the VSA function within OMASES is illustrated in figure 4.

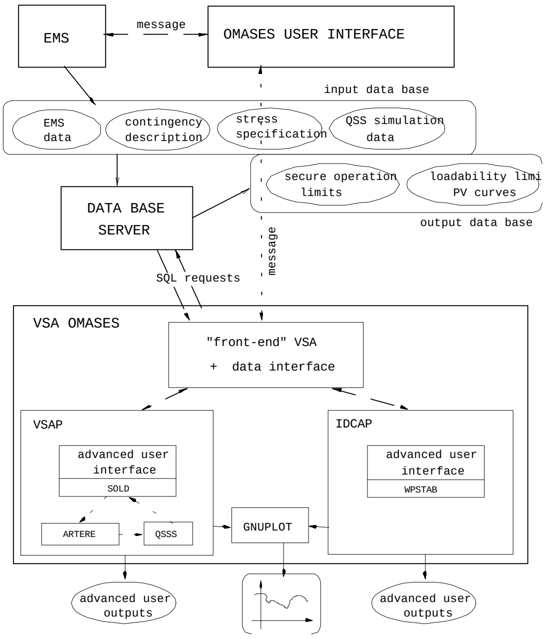

Fig. 4 – General layout of VSA in OMASES

Two programs are used within the context of the OMASES project :

- for VSAP purposes: ASTRE, developed at the University of Liège, and used by several companies and system operators [16];
- for IDCAP purposes: WPSTAB, developed at the National Technical University of Athens and licensed for use to the System Studies Department of the Hellenic Transmission System Operator (HTSO).

ASTRE is made up of three executables:

- ARTERE, a power flow program used to: (a) solve a base case, (b) stress the system in a pre-contingency situation, for instance to simulate an energy transaction in an open-access environment, (c) quickly filter out harmless contingencies at the first step a security limit determination.
- QSSS, a fast time-domain simulation program based on the QSS approximation, aimed at computing the system response to contingencies
- SOLD (Secure Operation Limit Determination): its aim is to compute SOLs with respect to contingencies. SOLD calls ARTERE to obtain the system state at various stress levels and QSSS to know if the post-contingency system evolution is acceptable with respect to user-defined criteria. Security limits are determined through binary search organized in different ways. Beside security limit calculation, analysis and diagnosis facilities are provided.

The ARTERE and QSSS computations are triggered by messages sent by SOLD. The (solved case) data are passed by ARTERE to QSSS through a shared memory.

WPSTAB produces the PV curves describing the post-contingency loadability limits. In particular a curve of the voltage at a representative bus as a function of total area load for the region affected by the most constraining contingency determined by VSAP is provided.

For both ASTRE and WPSTAB, other outputs are available from the advanced user interfaces of these packages. A variety of interfaces are made available to the advanced user in the form of text files, time plots and bar charts.

3.2.3 TS – Training Simulator for EMS Operators

The need for advanced training simulator for EMS operators is deeply felt as various elements like deregulation or environmental constraints make power grids operated closer to their limits and more difficult to operate [13], [15]. The "chances" for operators to face cascade tripping, interarea oscillations or voltage collapse are increasing. Restoration after major incidents is also a concern. Therefore training sessions must more and more integrate scenarios of such types. Moreover, new on-line tools of Transient Stability or Voltage Security assessment are based on the detailed modeling of the electromechanical dynamics of the system.

Validating these tools as well as teaching their efficient use to operators require to dispose of simulators whose capacity and accuracy allow for high fidelity simulation of any kind of dynamics along the scenarios to be played. Covering all these aspects in a versatile and robust way calls for serious changes in the traditional power system model of the training simulators that require the setting up of new numerical and algorithmic methods.

Performances are, of course, heavily dependent on the power system model and on operating mode. In the previous sections, apart from the Engineering mode, two further operating modes have been identified within OMASES: the real-time mode (that concerns the use of the DSA tool on-line with the SCADA system thus allowing a preventive approach to power system control and supervision) and the training mode (which is generally off-line) mainly devoted to prepare operators and make them suitably trained to front system disturbances. These two modes have different HMI and simulation speed requirements.

When *running on-line*, the simulator must be designed to play interactively any scenario starting from an actual operating point extracted from the SCADA and taking into account any kind of disturbances or operator actions. The HMI must provide all information needed to understand the phenomena and to implement counter measures.

When used in *training mode*, the simulator must run in real time, that is to say that the true state of the system must be displayed at the operator station according to the refreshment time of the SCADA (about 2 to 10 s). Of course, faster phenomena must be calculated in detail in order to simulate possible fast unstable behaviours, protection operation, etc.

To reach this twofold target, OMASES bases its developments on two different codes proprietary of Tractebel: EUROSTAG and FAST [13], [18].

The EUROSTAG program is a simulation tool development jointly with EDF. The software computes the so called “Extended Electromechanical Model” of the power system, valid in the range (0 - 10 Hz) (which corresponds to physical phenomena ranging from rotor transients up to daily load variation) and for large deviations from normal conditions (up to voltage or frequency collapse). The main breakthrough of EUROSTAG is its algorithm. Its implicit simultaneous method adapts automatically and continuously the stepsize in order to secure a constant simulation accuracy.

The FAST program has been developed to serve as real time simulation engine for dispatcher training simulators. FAST runs basically the same model of the power system as the one of EUROSTAG, with some limitations in the complexity of the component models. The integration algorithm is of the implicit simultaneous class too, but the time step is constant. Indeed, the real time constraint appears most challenging in case of fast behaviour of the system (like a loss of synchronism resulting from a short circuit). The algorithm is thus optimized to face this kind of phenomenon which request a time step in the range of 10 – 40 ms. Simulation time is synchronized to the real time at the SCADA discretization period, allowing for some flexibility in the computation time of an integration step.

On the basis of these two technologies, the developments described below will be pursued within OMASES.

A HMI environment suitable for DSA tools assessment and on line DSA diagnosis will be build around the simulation engine. The same software is also intended to educate operators to power system dynamics, on their own system. The HMI environment will consist of operator screens based on animated grid one-line diagrams and an operation engineer station allowing to display time-domain physical curves and to access the post simulation analysis modules of the simulation engine.

Instead, for the real-time training simulator, the operator screens will be very similar to the one of the on-line simulator. Several operator stations will be able to run independent processes with their own system state display and event control.

The instructor station will have, on top of the operator station capabilities, all the functions of the operation engineer station and also the capabilities of managing the scenario (fault settings, generator set-point changes, load shedding, breaker changes, taking and achieving snapshots, saving system state in OMASES data base, access to the scenario building tool, etc.).

All the operator and instructor HMI processes as well as the FAST simulation engine will be running on a single multi-processor computer. Inter-process communication will use a shared memory. This will avoid the complexity of process synchronization and IT-protocol burdens.

3.2.4 MS – Market Simulator within OMASES

This section describes the basic concepts, initial assumptions and principal requirements regarding the market simulator development as a part of the OMASES project. It reports the internal architecture and the external interfaces of the OMASES Market Simulator, accounting for different market structures.

The primary function of the MS within the OMASES environment is to build a generator dispatch for a defined future scenario on the basis of characterized markets. It also provides a facility for assessing the impact of various changes to an energy market (e.g. rule changes, participant changes). The MS will provide two types of dispatch namely, the unconstrained and constrained market dispatches. The primary difference between these dispatches is that the constrained dispatch will be unit and thermal constraint corrected.

The OMASES Market Simulator is the source of input data for further technical analyses to be conducted with other OMASES tools. For example the dispatch output can be used to drive a training session in the OMASES TS whose output can then be used by the OMASES TSA and VSA.

Using the existing data capabilities and functionality of the EMS, the OMASES subsystems will be employed to provide a more accurate assessment of stable power flows and limits within a deregulated market environment. It should be noted however, that the MS is not operating directly with the EMS within the OMASES project. As far as the MS is concerned, the EMS merely acts as a potential source of network states via the OMASES data base (DB), although the use of these states may be coupled through the scenario preparation capabilities of the OMASES TS.

The following separate modes of operation are identified for the MS:

- Market simulation configuration mode
- Simulation specification mode
- Unconstrained dispatch mode
- Constrained dispatch mode

The features of the simulator are configured for a particular market set-up in the market simulation configuration mode. Appropriate market simulator entities are selected and defined from the generic models, with details being stored in the OMASES DB.

In the unconstrained dispatch mode a market-based active power dispatch will result which does not take account of network constraints. While this is of no direct use with regard to delivering power, it does provide a use case for assessing what patterns of generation the market is producing without the “economic distortion”. Finally the constrained dispatch mode provides a constrained MW generation schedule taking account of steady state network constraints.

4. SET-UP OF THE EXPERIMENTATION SITES

The main objective of the Site Experimentation is to test the performances of the OMASES products in a real world environment. The OMASES platform will be used on-line at relevant sites. The two sites will be made available by the Hellenic Transmission System Operator (HTSO) and by CESI. They will respectively concern the EHV/HV Greek and Italian Transmission Systems. The validation will address the issues related to transient and voltage stability. The Greek site will also test the training simulator and the market simulator.

A very important feedback that the Consortium expects to be acquired during these tests concerns the possibility to receive comments and suggestions on the OMASES User Interface from system engineers and control room operators.

The two experimental sites are located at:

- Site 1: CESI, with remote connection to the Italian Transmission System Operator (GRTN – Gestore della Rete di Transmissione Nazionale)
- Site 2: Hellenic Transmission System Operator (HTSO)

With the aim of evaluating the performances of the DSA OMASES tool, requirements from CIGRE guidelines and prescriptions from the two TSOs involved in the experimentation phase have been compared for TSA and VSA. The following specific requirements have been adopted for the OMASES project.

Security assessment: contingency filtering, ranking and evaluation (stable/unstable, margins), for a list of contingencies selected by system operators or, alternatively, all “N-1” type of contingencies originated by pre-specified fault type (3-phase or single-phase) and at given fault clearing times. *ATC/TTC calculations*: for a number of source/sink patterns and the constraining contingencies (for example about 10 contingencies per ATC calculation. *Analysis of Preventive mode control* (including guidelines to the operator for preventive corrective actions): generation rescheduling and load-shedding.

The analysis and the final choice of the requirements adopted in OMASES are summarized in the following Table 2. The VSA OMASES computing times refer to all stress directions considered, provided that the appropriate number of available computers.

Table 2: Relevant performance constraints specific to TSA and VSA functions

TSA	CIGRE Guidelines	GRTN Requirements	HTSO Requirements	TSA OMASES Capability
Network size (nodes/lines/ generators)	1000/4000 /≈150	1000/2000/450	1200/1500/150	1500/2000/450
N. contingencies to filter	300	no more than 200	200	200
N. TTC sink/source patterns	-----	no more than 6 for “Italy-Rest of Europe” Interface no more than 3 for “Florence-Rome” Interface no more than 2 for “Sicily-Rest of Europe” Interface	10	11
N. Generators to shift	-----	no more than 20 for “Italy-Rest of Europe” Interface no more than 10 for “Florence-Rome” Interface no more than 10 for “Sicily-Rest of Europe” Interface	30	30
Cycle time	20 minutes	15 minutes	20 minutes	15 minutes
Execution time	1-2 minutes	5 minutes	1-2 minutes	< 15 minutes

VSA	GRTN requirements	PPC/HTSO Requirements	VSA OMASES capability
Network size (buses/lines/generators)	2000 / 2200 / 460	1200 / 1500 / 150	2000 / 2500 / 500
No. of contingencies before filtering	500	500	1000
No. of contingencies To study in detail	up to 40 for the “Italy- Rest of Europe” interface up to 15 for the “Rome-Florence” interface	Up to 40	50
No. of stress directions	up to 6 for the “Italy-Rest of Europe” interface up to 3 for the “Rome-Florence” interface 1 national load increase	1 national and up to 3 regional load increase patterns up to 3 corridor flows (N-S, E-W, between neighbouring systems)	distributed computing will be used when more than one direction of stress is required in real- time operation and if needed to meet the execution time requirements
Cycle time	30 minutes	30 minutes	30 minutes
Execution time	20 minutes	20 minutes	10 minutes

Available Transmission Capacity (ATC) calculations are an important result for both TSA and VSA functions, even if they should be integrated in some way in order to provide a coherent result for the power system ATC. Accuracy of ATC results may be anyway undermined by the lack of critical information, such as: consideration of ETSO-UCTE rules; probabilistic considerations for the definition of the Transmission Reliability Margin (TRM).

A further step in the setting up of the scenarios for the experimental phase of the OMASES project has been the analysis of the two systems that will be made available by the Italian TSO and the Greek TSO. The following scenarios will constitute the basis for the validation analysis.

(I) The Italian test site

The Italian power system is characterized by long transmission lines and stability constrained cut-sets. The electrical energy importation from abroad is particularly important. The interconnection with abroad is constituted by 15 tie lines of which 6 are 400 kV lines and 9 are 220 kV lines. The following three cases of stress patterns will be considered in the experimentation phase:

(a) increase of interface power flow from the rest of Europe to Italy. In this stress pattern the load will be left unchanged in Italy, where generation will be decreased. To this purpose, generators will be taken out of service step by step. To avoid creating voltage problems in the external equivalent (which are of little interest to the system under study), imported power will be increased by decreasing the loads in the external equivalent. Since the interface covers a wide geographical and electrical area, it is divided into three corridors: the French, the Swiss and the Austrian/Slovenian corridor. The generators to be taken out of service and the external loads to decrease will be specified in order to create different power flow distributions in the interface, for instance:

- balanced corridors: all lines of the corridors are equally loaded with respect to their thermal capability
- unbalanced corridors: the three corridors have different power flows.

The relevant, constraining contingencies for this stress are:

- the loss of 400-kV lines in the interface, or in series with the interface lines
- the loss of large power plants in Northern Italy
- the loss of 400-kV and 220-kV lines in Northern Italy.

Contingency filtering will be applied to this reduced set of contingencies. It will be of interest to compare the VSA limits with thermal overload limits with the associated risk of cascade line tripping leading to islanding, underfrequency load shedding or overfrequency unit tripping on the export side.

(b) increase of interface power flow between the Rome and Florence areas. This interface has five lines (three 400-kV and two 220-kV lines) and the flow is normally from North to South.

A similar procedure as for the first stress category, including contingency filtering, will be followed. The relevant, constraining contingencies for this stress are:

- the loss of 400-kV lines in the interface, or in series with lines in the interface
- the loss of large power plants in Central Italy.

(c) national load increase. Loads will be increased according to forecast patterns inspired by past situations. Load increase is compensated by generators according to secondary frequency control regulation. The participation factor of each generator in the load increase will be considered.

(II) The Greek (HTSO) test site

The following stress types and directions will be considered for the Greek Interconnected Power System:

(a) national load increase. Loads will be increased according to forecast patterns inspired by past situations, or given by EMS. All generators in operation, according to their participation factors, will compensate this load increase. Major contingencies, such as generators tripping (up to 10 contingencies) or 400 kV transmission lines switching (up to 10 contingencies), will be considered for this uniform stress.

*(b) South system load increase (Attica and Peloponnese).*The load increase will be enforced only in Attica and Peloponnese areas. All generators in operation, according to their participation factors, will compensate this load increase. Major contingencies, such as generators tripping (up to 5 contingencies) or 400kV/150kV transmission lines switching (up to 10 contingencies), on the North – South axis, will be considered for this stress.

(c) increase of power flow to Peloponnese area. In this stress, the load of the Hellenic Interconnected Power System will be left unchanged. The generation of Peloponnese area units (located at Megalopoli) will be decreased. By this stress it is possible to compute the must-run generation in the area. Up to five (5) constraining contingencies are considered for this stress.

(d) increase of power flow into Attica area. In this stress, the load of the Hellenic Interconnected Power System will be left unchanged. The generation of Attica area units (Laurio and Ahsag units) will be decreased. By this stress it is possible to compute the must-run generation in the area. No constraining contingencies are considered for this stress.

(e) increase of power flow from/to Italy. An asynchronous interconnection 400-kV (AC-DC-AC) interconnects the Hellenic and Italian power systems. In this stress, the load of the Hellenic Interconnected

Power System will be left unchanged while its generation will be decreased/increased to model import/export of power according to relevant participation factors of the generators. The relevant constraining contingencies deal with the loss of generation in the West system for this stress (up to 5 contingencies).

(f) increase of power flow from/to the Balkans. The Hellenic Interconnected Power System is interconnected via three 400-kV tie lines to the Balkan countries (Albania, Bulgaria, and FYROM). In this stress, the load of the Hellenic Interconnected Power System will be left unchanged. The generation of the Hellenic power system will be decreased/increased in case of import/export according to the participation factors of the generators. Three constraining contingencies are considered for this stress.

5. CONCLUSIONS

The paper has reported a detailed overview of the OMASES project, an industrial-research project in the field of dynamic security assessment of large power systems. The definition of requirements for an advanced DSA tool to be integrated into EMS has been reported together with the main bases for the application functions included in OMASES.

The major goals for OMASES related to power system operation are to provide an automated methodology for dynamic security assessment and to increase power flows on electrical transmission lines. These goals are achievable through on-line TSA and VSA provided by advanced software developed and made available to the Consortium. Direct connection to EMS environment makes it possible to provide operators with suitable functions for improving and guaranteeing system security in a preventive mode.

OMASES can furthermore be used off-line as an advanced educational tool for training system operators by integrating the DSA functions with a powerful Training Simulator and a Market Simulator.

The validation phase of the prototype at two sites is expected to provide important feed-backs for the realization and/or tuning of DSA tools capable of fitting with the needs posed by the important changes that have occurred in power system operation and management.

6. BIBLIOGRAPHY

[1] *Proceedings of the IEEE*, Special Issue on the Technology of Power System Competition, Vol. 88, No. 2, February 2000

[2] M. D. Ilic, F. Galliana, L. Fink: *Power System Restructuring*, Kluwer Academic Publishers, Boston, Dordrecht/London, 1998

[3] T. Dy Liacco, "Enabling Technologies for Operation and Real-time Control in a Liberalized Environment", EPRI – Second European Conference on EMS, Budapest, November 1999

[4] M. Pavella, D. Ernst, D. Ruiz-Vega, "Transient Stability of Power Systems - A unified approach to assessment and control", Kluwer's Power Electronics and Power Systems Series, October 2000

[5] OMASES - *Open Market Access and Security Assessment System*, EU Contract N. ENK6-CT2000-00064, December 2000

[6] Task Force CIGRE 38.02.13, "New Trends and Requirements for Dynamic Security Assessment", *Electra*, No. 175, December 1997

[7] Task Force CIGRE N. 17, AG 02, Subcommittee 38, Advanced Angle Stability Controls, CIGRE Technical Brochure, Final Draft, October 1999

[8] F.A. Rahimi, N.J. Balu, M.G. Lauby, "Assessing on-line Transient Stability in Energy Management Systems", *IEEE Computer Applications in Power*, Vol. 4, No.3, July 1991, pp. 44-49

[9] K. Demaree, T. Athay, K. W. Cheung , Y. Mansour, E. Vaahedi, A.Y. Chang, B.R. Corns, B.W. Garrett, "An On-line Dynamic Security Analysis System Implementation", *IEEE Transactions on Power Systems*, Vol. 9, No. 4, November 1994, pp. 1716-1722

[10] M. Pavella, L. Wehenkel, Y. Zhang, "SIME: A hybrid approach to fast transient stability assessment and contingency selection", *Electric Power & Energy Systems*, Vol. 19, No. 3, 1997, pp. 195-208.

[11] T. Van Cutsem, C. Vournas, "Voltage Stability of Electric Power Systems", Kluwer Academic Publishers (Power Electronics and Power Systems Series), Boston, 1998

[12] D. Cirio, S. Massucco, A. Morini, F. Silvestro, L. Polese, R. Salvati, F. Casamatta, G. Demartini, P. Scarpellini, "A decision support system for preventing power system degradation into emergency conditions", IEEE ISAP 2001 Conference, Budapest, June 18-21, 2001

[13] S. Gissinger, P. Chaumes, J-P. Antoine, A. Bihain, M.Stubbe: "Advanced Dispatcher Training Simulator", IEEE Computer Applications in Power, Vol. 13, No 2, 2000, pp. 25-30

[14] P. Baratella, P. Scarpellini, R. Marconato, B. Cova, E. Gaglioti, R. Zacheo, "A Power System Simulator Covering Different Time Scale Phenomena: Models, Algorithms, MMI and Test Results", Proc. IEEE Stockholm Power Tech, Stockholm, June 1995, pp. 376-381

[15] M.A. Pai, *Energy Function Analysis for Power System Stability*, Prentice Hall, Englewood, New Jersey, USA, 1992

[16] D.Ernst., D. Ruiz-Vega, M. Pavella, P. Hirsch, D. Sobajic, "A Unified Approach to Transient Stability Contingency Filtering, Ranking and Assessment",.. IEEE Transactions of Power Systems, Vol. 16, No. 3, August 2001

[17] T. Van Cutsem, F. Capitanescu, C. Moors, D. Lefebvre, V. Sermanson, "An advanced tool for preventive voltage security assessment", Proc. 7th Symposium of Specialists in Electric Operational and Expansion Planning (SEPOPE), Curitiba (Brazil), May 2000

[18] M. Stubbe, A.Bihain, J.Deuse, J.C. Baader, "STAG - A New Unified Software Program for the Study of the Dynamic Behaviour of Electrical Power Systems", IEEE Transactions on Power Systems, Vol. 4, No 1, 1989, pp.129-138