Voltage Stability Assessment for a Realistic Power System: the Italian Case

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Abstract- **This paper describes the fundamentals of the Voltage Stability Assessment (VSA) approach adopted in OMASES, an integrated platform for Dynamic Security Assessment, and its application to a realistic grid model, namely the Italian national grid. In the first part the authors illustrate the Quasi Steady State (QSS) method and the calculation of the Secure Operation Limits (SOLs) by means of the OMASES module VSAP. In the second part the grid under test is examined and the VSA process is described: several contingency scenarios are built, considering n-1 and n-2 contingencies related to the loss of lines and generators and applying two different stress directions. Finally, results of the analysis are shown and commented. In case of low security margins also the necessary load shedding actions are calculated and illustrated.**

Keywords- Power System Security; Voltage Stability; Load Shedding; Contingency Ranking; Operational Margin; On-Line Security Assessment

I. INTRODUCTION

The high exploitation of the grid and increasing uncertainties in load and generation profiles, induced by the liberalised market [1] and by renewable generation, reduce the security margins, which is demonstrated by the occurrence of several blackouts in early 2000's [2, 3].

To this regard, many experts [4] pointed out that the load is a large, underused and often underestimated resource that could be exploited in a better way to provide economic benefits and more reliability. In particular, load control can enhance the security of operation. Several applications have been proposed, e.g. the use of Interruptible Loads (ILs) for voltage stability [5], [6]. In the cited works the analysis was performed by means of OMASES (Open Market Access and SEcurity assessment System), a Dynamic Security Assessment tool developed within an EU partially funded research project [7, 8]. Besides the better exploitation of loads, another issue to be investigated consists in a more accurate identification of the actual security margins of power systems. The voltage stability assessment approach of OMASES is intended to tackle such a problem.

Historically, Transient Stability Assessment (TSA) has been probably the main concern of system operators and analysts up to few decades ago [9-11]. On the other hand, Voltage Stability Assessment is a more recent topic, whose importance has rapidly grown in last decades as power systems became more and more stressed and congested [12-16]. Determining the maximum permissible loading within the voltage stability limit has become a very important issue in power system operation and planning studies. The conventional P-V or Q-V curves are usually used to assess voltage stability and hence to find the maximum loading at the verge of voltage collapse. These curves are generated by running a large number of load flow cases using conventional methods. While such procedures can be automated, they are time-consuming and do not readily provide information useful in gaining insight into the cause of stability problems.

To overcome the above disadvantages several techniques have been proposed in the literature, such as bifurcation theory, energy methods, eigenvalue and singular value methods [13]-[17], multiple load flow solutions method, etc.

They are computationally intensive, which makes them less viable for fast computation during a sequence of discontinuities like generators hitting field current or reactive limits, tap changer limits, switchable shunt capacitor susceptance limits etc. In a dynamic voltage stability computation regime, it is necessary to consider all these discontinuities into the analysis. Moreover, a quick computation is necessary to take the necessary corrective actions in time to save the system from an impending voltage collapse.

The main goal of VSA is to avoid the phenomenon known as "voltage collapse". Voltage collapse is a many-faceted occurrence, both in terms of time-frames and of causes, and it has been thoroughly investigated in [13]-[16]. Voltage collapse is usually a load-driven phenomenon, since reactive power scarcity is generally originated by reactive power demand increase.

One of the most promising approaches to quantitatively assess voltage stability margins and to get a deeper insight into voltage stability issues is adopted by the DSA tool implemented within the OMASES project. The goal of the project was to provide TSO operators with a DSA platform to be used on-line during the normal real-time operation, in operational planning and as a dispatcher training simulator including a simplified simulation of electric market environment. Two experimentations sites were set up, in which OMASES was connected respectively to the EMS of the Hellenic TSO and, by a remote connection, to the EMS of the Italian TSO [8]. DSA within OMASES is carried out through different application functions: TSA, VSA, TS—training simulator, and MS—market simulator. OMASES can be "plugged" into existing EMS or engineered into new EMS structure as it essentially uses a LAN-based architecture for inter-machine communications allowing easy hardware and software integration.

The VSA application function [18] integrates software tools for the assessment of voltage security within the platform. VSA 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 [11].

The paper is structured as follows. Section II presents the main features of OMASES approach to VSA. Section III presents voltage stability analyses for the Italian power system performed via the OMASES VSA function application: in particular, simulation results are discussed, followed by general conclusions in Section IV.

II. OMASES APPROACH TO VSA

The present section recalls the OMASES module devoted to in-depth voltage stability analysis, namely VSAP (Voltage Security Analysis Package)/ASTRE. As VSAP relies on Quasi-Steady State (QSS) simulation [16], [18], this technique is preliminary introduced.

A. Quasi-Steady State Simulation

The Quasi-Steady State method stems from the consideration that most physical systems (and particularly the electric system, as mentioned above) have dynamics evolving over different time scales. It is thus possible to separate faster phenomena from slower ones, performing the so-called time-scale decomposition.

The core of QSS approximation consists of representing faster phenomena by means of their equilibrium conditions instead of their full dynamic representation. Since voltage stability is mostly driven by the long-term evolution, decomposition can be applied by representing the short-term subsystem conditions at equilibrium: generators, speed governors and Automatic Voltage Regulators (AVRs) are described by their steady-state (i.e. algebraic) equations. Instead, the long-term dynamics are described either by differential equations or by discrete time equations. The time-scale decomposition allows a dramatic increase in computational efficiency so that it is possible to handle thousands of contingencies on a realistic power system in less than 5 minutes: this makes it suitable for on-line VSA sessions within EMS environment. A detailed description of this methodology can be found in [16].

B. Overview of the VSAP Module

It has been recalled that an effective measure of system robustness to voltage stability issues is provided by the loadability margin according to different stress directions. However, in order to obtain an in-depth evaluation, the dynamics affecting voltage stability should be considered, as well as the system response to credible contingencies. VSAP precisely addresses these requirements: its main goal is to compute Secure Operation Limits (SOL) with respect to certain stress directions and a pre-defined set of likely conditions; further, analyses rely on QSS dynamic simulation. 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.

Other remarkable objectives of VSAP are:

- to evaluate the impact of contingencies on the voltage behavior of the system
- 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.

C. Secure Operation Limits Determination: Binary Search and Simultaneous Binary Search

A Secure Operation Limit is a number in MW which indicates how much a system can be stressed, still being able to sustain a number of pre-defined contingencies. In other words, if the system is stressed by increasing its load (and consequently also modifying generation) by an amount of MW not greater than the SOL, it will respond satisfactorily to any contingency within the specified set, i.e. it will remain stable and without violations of current or voltage limits. A SOL is thus associated with a stress direction and a contingency set.

In general terms, a stress is originated by a change in load and generation that makes the system weaker. Depending on the location of the loads and the generators causing the stress, it is possible to obtain certain stress directions (also called stress patterns). Within the scope of SOL determination, one quantitatively defines the stress as the amount of load increase (or of generation decrease) in a certain area, covered by a corresponding generation increase in another area, according to the specified stress direction. The OMASES database contains some tables that allow the user to define load zones and generation zones (e.g. North generators, South generators, North loads, South loads, etc.) so as to specify the desired stress directions.

The contingency set is a series of pre-defined contingencies, where the user can insert such events as line outages, equipment failures, etc. It is possible to create different contingency sets in the database, for instance preparing a set of N–1 contingencies and a set of N–2 contingencies.

In order to perform SOL computations, the user has to specify a stress direction, a value of maximum stress S_{MAX} and a set of contingencies. Determination of the SOL for a single contingency relies on the so-called binary search [16]. It consists of identifying, by successive refinements, intervals $[S_l, S_u]$ where S_l is a pre-contingency stress for which the post-contingency state is stable, while for S_u the system evolves to instability. As the iterations proceed, these $[S_l, S_u]$ intervals get smaller and smaller (the interval at the *i*-th iteration is half the one at the previous iteration); when, at a certain step, the size of the interval is smaller than a chosen tolerance D, the algorithm stops and the relative S_l is declared as the SOL. Otherwise, the interval is divided into two equal parts: if the midpoint is deemed stable by the QSS simulation, it becomes the lower bound of the new interval, while if it is unstable it will be the new upper bound. Fig. 1 shows how the algorithm works.

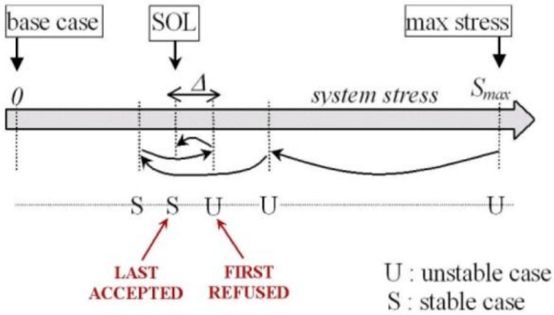


Fig. 1 Binary search of the SOL for a single contingency

The procedure starts from a base case (usually with no stress) and then applies a stress equal to S_{MAX} (this means that S_l =0 and $S_u = S_{MAX}$ at the first step). A QSS simulation is then performed at this new stress level: if the system turns out to be stable, the process is stopped and the SOL is declared equal to S_{MAX}; otherwise, if the case is unstable, the system is stressed at $S_{MAX}/2$, and the new interval is $[0, S_{MAX}/2]$ and so on.

This algorithm can be extended to many contingencies. A very time-consuming solution would be to repeat the whole procedure for each contingency within the set, but, since contingency sets (especially N–2) usually feature a large number of contingencies, it was decided to implement the so-called Simultaneous Binary Search (SBS). At the *i*-th iteration SBS simulates only the contingencies that have not been discarded at the previous one. A contingency is discarded if it is stable, provided that there is at least an unstable contingency: in fact, since it is stable at a certain step, its SOL is greater than that of the unstable contingency(-ies), and thus, in terms of detection of a SOL, it is less restrictive than the unstable one(s). Fig. 2 features an example of SBS with a set of four contingencies.

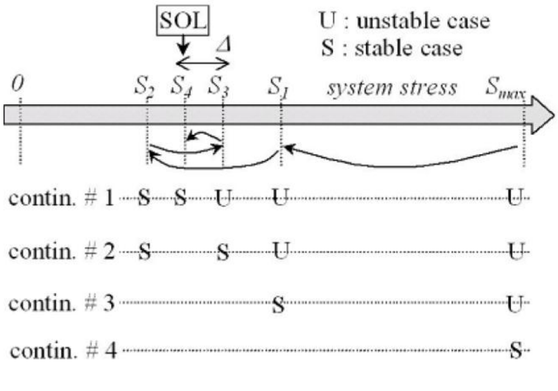


Fig. 2 Simultaneous Binary Search for four contingencies

Starting from the initial unstressed case, the system is stressed to S_{MAX}. Among the four contingencies, #4 is stable, so it is discarded. At S_1 (i.e. the midpoint between 0 and S_{MAX}), #3 is stable and then discarded. At the next step, corresponding to stress S_2 (i.e. the midpoint between 0 and S_1), both the remaining contingencies, #1 and #2, are stable, but they are not discarded, since there is no unstable contingency left. The interval is now $[S_1, S_2]$; at its midpoint S_3 contingency #2 is stable while #1 is not, so #2 is discarded and the process goes on with #1. The procedure ends at S_4, since the size of the interval $[S_4, S_3]$ is smaller than the tolerance D.

It is evident that the SBS converges to the most restrictive contingency: in the example, #1 is the most dangerous contingency, being its SOL S_4 smaller than all the stress levels which resulted in instability for all the other contingencies. Consequently, S_4 is the SOL for the whole set of contingencies, with respect to the applied stress direction.

D. Contingency Filtering

SBS is a fast and robust algorithm for determining the SOL for a set of contingencies; though, if the set is made by many contingencies, the computation may still be heavy. The first step of the SBS is in itself a contingency filtering: all the disturbances secure at S_{MAX} are discarded. As this screening may not be enough, a pre-filtering is applied before the first step of the SBS. The technique used for this pre-filtering is the post-contingency load flow. Contingencies are applied to the S_{MAX} case: those presenting a load flow solution with no violation in the operating quantities are discarded.

Load flow equations with constant power loads and enforcement of generator reactive limits correspond to the long-term equilibrium that prevails after load voltage restoration by On-Load Tap Changers (OLTC) and machine excitation limitation by over-excitation limiters (OEL). Insofar as voltage instability results from the loss of such an equilibrium, the corresponding load flow equations no longer have a solution and the Newton-Raphson algorithm diverges. However, using load flow divergence as an instability criterion meets the following difficulties:

1) Divergence may result from purely numerical problems (this is particularly true when controls have to be adjusted and/or many generators switch under limit)

2) Some dynamic controls that help stability cannot be accounted for in the static load flow calculation

3) Conversely, some system dynamics may be responsible for an instability not detected by the load flow

The first two inaccuracies may lead to overrating the hazard of the contingency: some safe contingencies could be deemed as dangerous by the load flow filtering and so they would not be discarded, with some unneeded computational effort for the SBS. The third possible error may discard some dangerous contingencies. Clearly, incurring in this last event is much worse than not filtering some safe contingencies. Thus, a contingency is considered harmful also if some post-contingency voltages fall below some value, and not only if it makes the load flow diverge.

In order to have an accurate post-contingency load flow filtering, and to reduce the three possible errors just pointed out, it is necessary that its data match as closely as possible the model used in QSS simulation; in particular,

- generator reactive power limits must be updated with the active power output and terminal voltage
- any active power imbalance (caused by a generator tripping or a loss of connectivity) must not be left to the slack-bus but distributed over the generators according to frequency control

III. TEST CASE AND SIMULATIONS

The results hereafter presented were obtained with the off-line mode (or study mode) of OMASES, however all the considerations may be easily extended to real time operation (i.e. with OMASES plugged into an existing EMS and processing on line data). An on-line application of the OMASES VSAP tool [18] in the EMS environment has been carried out by the Hellenic TSO; in real time mode, OMASES-VSA is coupled to the real-time EMS system. Thus, although the period of execution of OMASES-VSA is in the range of every 5-10 minutes, this mode is referred to as the real-time mode. In this configuration, the EMS feeds OMASES-VSA with network state estimator solutions. The execution of the VSA functions is periodic and triggered automatically by the data transfer from the EMS. More precisely, an EMS process periodically creates 14 text files containing the latest network solution computed by the state estimator. Each file is a description of a class of EMS components (e.g. substations, nodes, buses, lines, transformers, generators, loads, etc.) and corresponds to a table of the VSA relational database. These files are sent by the same EMS process to a predefined real-time entry directory of the VSA server, which triggers the VSA computation cycle. The VSA tool based on QSS simulation has been also used for post mortem analysis of 2004 Greek blackout, and to evaluate most effective countermeasures to be deployed [19].

A. Test System: the Italian 380 kV / 220 kV Network

The network used as testing ground for OMASES is the Italian transmission system model of early 2000's. The representation of the network includes the two voltage levels 380 kV and 220 kV, as usual for EHV power system studies.

In order to test OMASES on a particularly stressed network configuration, it seemed reasonable to choose a peak load situation. Specifically, the EMS snapshot considered is a summer peak configuration. In fact since 2003 Italy has been basically a summer peaking country, mainly due to a large use of air conditioning and ventilation systems [2].

B. Building up a Suitable Scenario

The starting scenario for the application refers to June 18, 2003, 10:45 a.m. In order to perform the analysis, a scenario (i.e. the combination of a system configuration and operating point, stress direction, contingency list) must be set up.

Compliance with security rules implies that operating points (even during peak situations) are usually appropriately far from emergency conditions. Thus, it was necessary to modify the starting scenario to get closer to dangerous situations. Moreover, some changes to the real data of the generation outside Italy were necessary. The next sections will discuss all the modifications made on the original data.

1) Modeling Foreign Generators:

The data regarding Italian generators are well established and reflect exactly the real configuration of Italian plants. For foreign generators, it is common practice for system analysis to model as accurately as possible only those generators which are closer to the system under study, because they are the ones which more likely affect the behavior of the concerned system, and to allow a lower level of detail for the far ones. Thus, far generators are usually merged into large equivalent generators ("External Equivalent").

Therefore, when setting up the OMASES scenario, the generators closer to the Italian border (i.e. France, Switzerland, Austria, Slovenia) were modeled as accurately as possible. Among them, the largest units (with a power rating larger than 900 MVAs) were modeled as negative loads, i.e. as fixed power injections, so that they do not participate in the stress scenario (load increase is compensated by other units).

2) Choosing Stress Directions:

As pointed out in the previous section, a leading force in voltage stability issues is the increase in power consumption by loads. Usually, load consumption is forecast on a day-ahead framework on the basis of statistical data regarding power consumption in analogous days of previous periods. Obviously, the prediction also considers those variable factors that do influence power consumption, such as weather conditions, social and economic situations, etc.

When building the scenario for testing OMASES VSA, two stress directions (or patterns) were considered, namely Uniform stress and External stress.

The Uniform stress is probably the simplest stress configuration that may be considered: the national load is increased uniformly, i.e. in every area, and the resulting mismatch is covered by national generation.

The External stress is obtained as follows: again, load increase is made on a national basis, but this time the mismatch is covered by foreign generators. This kind of stress was set up in order to simulate a condition of high power flows on the interconnection lines between Italy and the rest of Europe, a frequent operating condition some years ago more than today.

3) Choosing Contingency Lists:

The choice of significant contingency sets is again important, as the SOL is computed in relation with a stress direction and a set of contingencies.

Four contingency sets were defined, and specifically:

- Set_1_n-1: each contingency of this set consists of tripping one line on the Italian transmission network. The chosen lines are not the complete set of 380/220 kV transmission lines of the Italian network (the contingency set would be huge!); the set is composed by 64 lines located on some critical sections of the network
- Set_1_n-2: each contingency of this set consists of tripping two lines, the second one 250 seconds after the first one. Thus, each contingency of the set is an "n-1-1" double contingency (in the following, simply referred to as "n-2"). The chosen lines are again the 64 lines of the previous set, and they are combined in pairs so as to obtain the 221 contingencies that constitute this set
- Set_2_n-1: each contingency of this set consists of tripping one generator of the Italian system. The chosen generators are the complete set of 311 machines connected to the 380/220 kV Italian network
- Set_2_n-2: each contingency of this set consists of tripping two generators, the second one 250 seconds after the first one. The generators chosen are a subset of the 311 Italian generators, and specifically the generators having Snom>700 MVA. They are combined in pairs so as to obtain the 306 contingencies that constitute this set

4) Building up the Simulations:

Having built two stress directions (Uniform and External) and four contingency sets (set_1_n-1, set_1_n-2, set_2_n-1, set_2_n-2), eight simulation cases were prepared by combining stress directions and contingency lists.

For each case, the procedure is the following:

1. MRS (Maximum Reachable Stress) Determination: By means of the OMASES VSAP module, the "loadability" (i.e. maximum reachable stress) of the system is computed, with regard to a stress direction (Uniform or External). No contingency is considered: the MRS simply says how much the load can be increased with integer system. Clearly, simulation cases having the same stress and differing only in terms of contingency set do have the same MRS.

2. SOL Determination: by means of the OMASES VSAP module, the SOL is computed, with regard to the stress and the contingency set of the case under examination. OMASES ranks the contingencies of the set on the basis of their margin.

3. Load shedding: for those contingencies having a margin smaller than 1,000 MW, an appropriate counteraction (load shedding) is proposed. The contingencies with a margin greater than 1,000 MW are filtered out, as considered not dangerous.

OMASES determines the amount of load to be shed as follows [18]:

a) A pre-contingency stress of 1,000 MW is applied to the system

b) Each contingency considered dangerous by the SOL determination (i.e. those contingencies having a margin smaller than 1,000 MW) is applied to the stressed system

c) The minimal amount of load to be shed is computed for each contingency so as to avoid voltage collapse or voltages smaller than 0.7 p.u. on each bus of the network. It is assumed that loads all around Italy are available for shedding.

In other words, after computing the MRS in Step 1 of the procedure, Step 2 essentially performs a SOL analysis on the system, presenting the typical outputs of OMASES (margins, Q reserves, voltage evolutions, voltage profiles).

On the other hand, Step 3 performs a load shedding analysis: it shows how much load (if any) has to be shed so that the system, after a pre-contingency stress of 1,000 MW, can sustain each contingency of the set. The meaning of this load shedding is twofold: from one point of view, it means that, if the system is stressed by 1,000 MW, the load shedding will make it able to resist every contingency of the set. From another point of view, it means that if the system is not stressed (i.e. it is in the base case) the same amount of load shedding will provide some security margin.

C. Simulation Results

Results are presented and discussed in this subsection. For sake of clarity, the simulations were numbered in accordance to combination of the type of stress (Uniform and External) and the contingency set (set_1_n-1, set_1_n-2, set_2_n-1, set_2_n-1), providing 8 simulation sets (Sim 1 to Sim 4 for Uniform stress and Sim 5 to Sim 8 for external stress). Anyway only the significant simulations will be reported and in particular:

- Uniform stress (namely Sim 1, Sim 2)
- External stress (namely Sim 5, Sim 8).

In terms of MRS, the Uniform stress (MRS=2,734 MW) is less dangerous than the External stress (2,148 MW). The External stress is basically an ideal concept used to reproduce a situation of increased import, since it is unrealistic to cover an increase of Italian power consumption only by means of external generation.

In any case, a MRS of 2,734 MW means that, also in a peak day, there is enough reserve to cover a large increase of load. Though, an (n-1 or n-2) contingency analysis is necessary to assess the security of the system and to see how much it can be really stressed.

1) Sim1 (Uniform Stress, set_1_n-1):

This simulation essentially assesses the n-1 security of the uniformly stressed system, with regard to a set of line tripping contingencies. Fig. 3 presents the bar diagram of the margins (i.e. the SOLs) for the most severe contingencies.

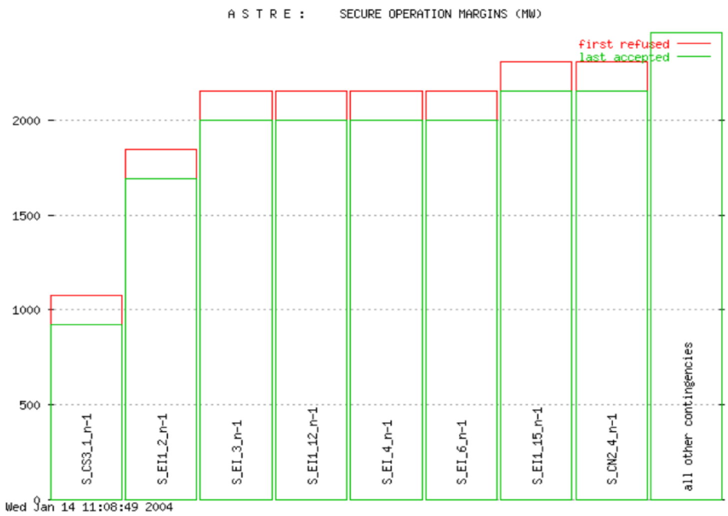
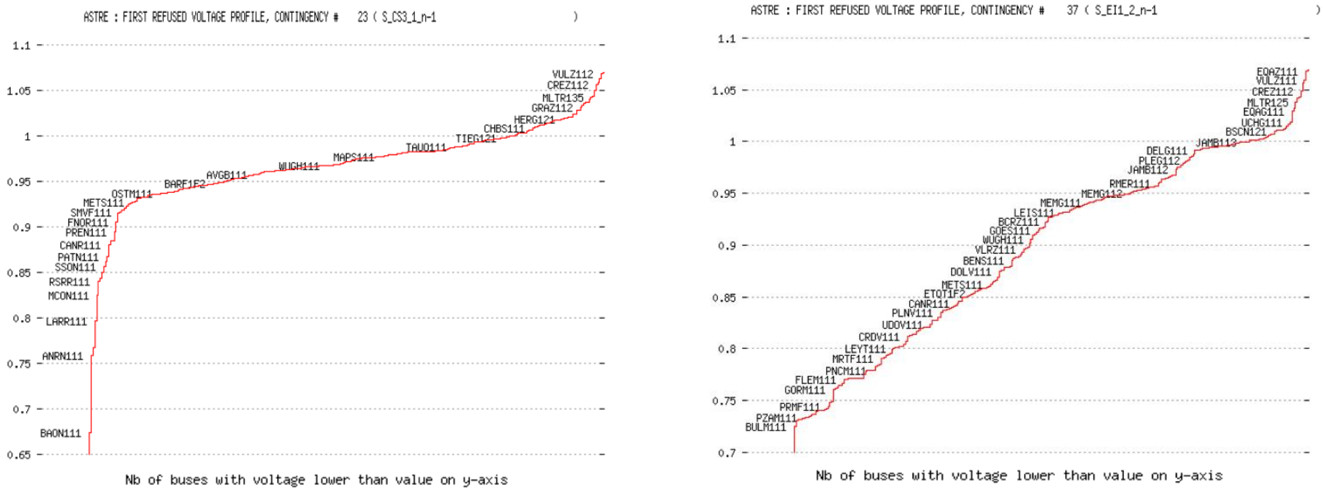


Fig. 3 Margins for Sim1

Since the Italian network is normally operated in (at least) n-1 security, all the contingencies of the n-1 set do have a margin (if they had not, the system would not be in n-1 security in the unstressed case). Among the 64 contingencies of this set, only two have a margin smaller than 2,000 MW, and the next four have a margin of 2,000 MW. The most risky contingency is S_CS3_1_n-1, which is the loss of the line connecting Brindisi to Bari, in the South of Italy. This result is expectable, since the area of Brindisi is known to be a problematic one, both for voltage and transient stability.

The remaining dangerous contingencies pertain interconnection lines with the neighboring countries, or lines with huge flows close to the interconnection. This result makes sense, as the analyzed situation was characterized by a large power import.

Another typical output of OMASES is the first refused voltage profile, which is basically a snapshot of the collapsing system at the marginally refused stress. This output is very useful for better understanding the dangerousness of a contingency, since it shows whether its effects are local or system-wide. Fig. 4a shows this kind of plot for contingency S_CS3_1_n-1, i.e. the one with the smallest margin.



(a) (b)

Fig. 4 Voltage profile for: (a) contingency S_CS3_1_n-1 (Sim1); (b) contingency S_EI1_2_n-1 (Sim1)

Clearly, the information that can be inferred by this plot is that the contingency has a local effect, since the most depressed nodes are in the area of the lost line: BAON111 (Bari), ANRN111 (Andria), LARR111 (Larino), MCON111 (Montecorvino).

The second contingency in terms of small margin, i.e. S_EI1_2_n-1, has a wider effect than the previous one, since more buses are depressed, as it can be seen in Fig. 4b.

Also the other dangerous contingencies have wider effects. Though, being the margins relatively high (all above 1,000 MW, except for S_CS3_1_n-1), there is no need for load shedding: S_CS3_1_n-1 is the only contingency not filtered out, since it is the only one with a margin smaller than 1000 MW, but the load shedding procedure suggests that no load shedding is needed for it (in fact, its margin is 923 MW, which is not too smaller than 1,000 MW).

2) Sim2 (Uniform Stress, set_1_n-2):

This time the n-2 security of the uniformly stressed system is assessed, with regard to a set of line tripping contingencies. Fig. 5 shows the margins (i.e. the SOLs) for the most severe contingencies.

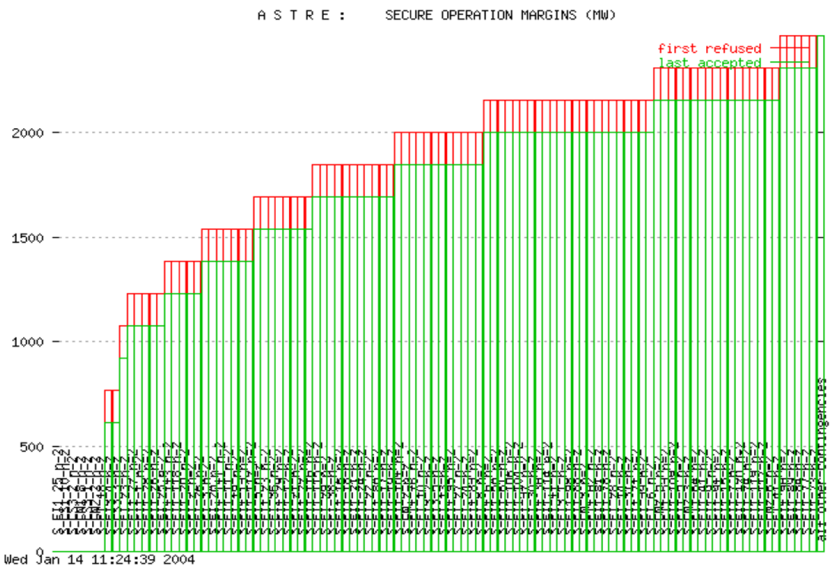
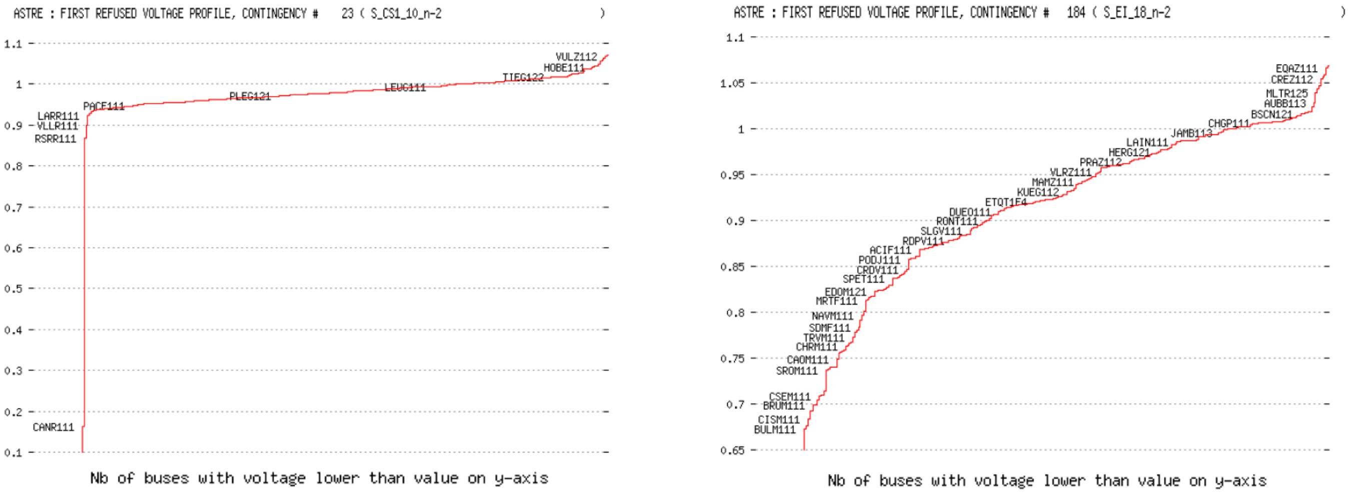


Fig. 5 Margins for Sim 2

First of all, it can be noticed that seven contingencies do not have margin. This means that, even in the base case (i.e. unstressed), the system cannot survive these contingencies. The base case under analysis is not in n-2 security. The dangerousness of this scenario is also shown by the fact that, apart from the seven no-margin contingencies, there are more than 50 contingencies with a margin lower than 2,000 MW.

Most of the seven contingencies, concerning line trippings mainly on the Centre-North or Centre-South corridors, have a local effect, and the affected area is always around the node of Candia in the Center of Italy. Again, this is no surprise and OMASES correctly diagnoses the situation: the area of Candia is known to be affected by voltage problems. Fig. 6a draws an emblematic case.

On the other hand, contingency S_EI_18_n-2, consisting of the loss of two lines on the interconnection with neighbouring countries, has a wider effect (Fig. 6b).



(a) (b)

Fig. 6 Voltage profile for: (a) contingency S_CS1_10_n-2 (Sim 2); (b) contingency S_EI_18_n-2 (Sim 2)

As for the load shedding analysis, Sim 2 features ten contingencies with a margin smaller than 1,000 MW; for these contingencies, an optimal load shedding research is performed by VSAP, not only to restore some security margin, but also in the case of the seven contingencies with no margin - to make the system able to survive the contingency at no stress. table I presents the results of the load shedding analysis.

TABLE I LOAD SHEDDING RESULTS FOR SIM2

Contingency	Margin [MW]	Shedding Amount	
		[MW]	[MVAR]
S_EI1_25_n-2	0	632.8	137.9
S_CS1_10_n-2	0	54.7	8.5
S_CS3_2_n-2	0	>2000	-
S_CN1_8_n-2	0	46.6	3.7
S_CS3_1_n-2	0	-	-
S_CN2_2_n-2	0	80.1	8.8
S_EI_18_n-2	0	832	197.8
S_EI3_4_n-2	615	84	11.2
S_CS3_3_n-2	615	668	215.4
S_EI_23_n-2	923	9.8	11.7

The load shedding procedure assumes that 30% of the load at each bus of the system is available for shedding, for a total amount of 2,000 MW of load available for shedding, distributed all around Italy. For each of the aforementioned ten contingencies, the third and fourth columns of table I show the minimum (optimal) amount of load to be shed in order to avoid voltage collapse or voltages smaller than 0.7 p.u. It can be noticed that in some cases even a small amount of load shedding is enough, while in others it is necessary to shed more. There are many factors that influence the optimal amount of load shedding, one of the most influent being the location of the available load. Usually, the closer the load to the contingencies, the better. This is even truer when dealing with voltage problems, as voltage problems are usually local issues.

In one case (contingency S_CS3_2_n-2) the total amount of 2,000 MW is not enough to avoid instability and/or low voltages. In such case, which is again localized in the Brindisi area and is essentially a local problem (see Fig. 7), a more localized load shedding would have probably been able to avoid problems.

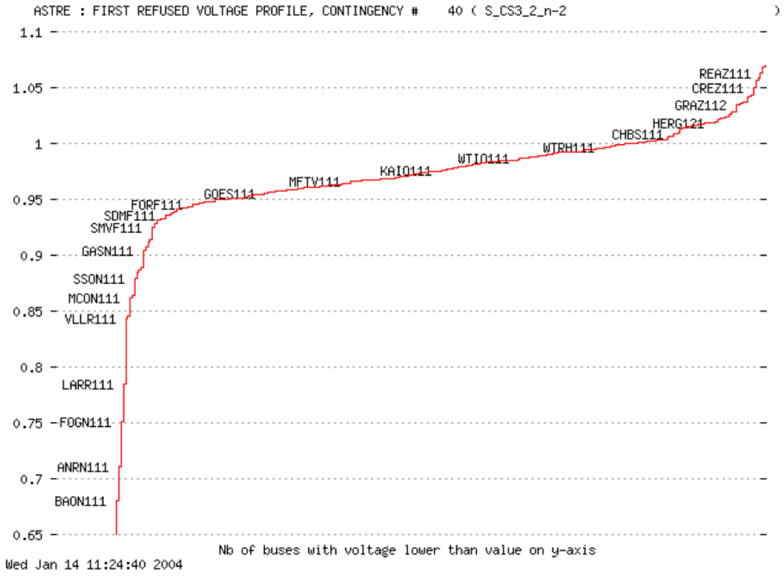


Fig. 7 Voltage profile for contingency S_CS3_2_n-2 (Sim 2)

Another contingency, S_CS3_1_n-2, was not stabilized by the load shedding analysis. This time, the problem was not the insufficient amount of available load. The analysis for this contingency stopped because of transient (angle) problems. This means that, for this contingency, a TSA analysis is needed.

3) Sim 5 (External Stress, set_1_n-1):

Sim 5 evaluates the SOL with respect to set_1_n-1 (the same set as in Sim 1); however, in this simulation the stress is external instead of uniform. Fig. 8 presents the results of this simulation.

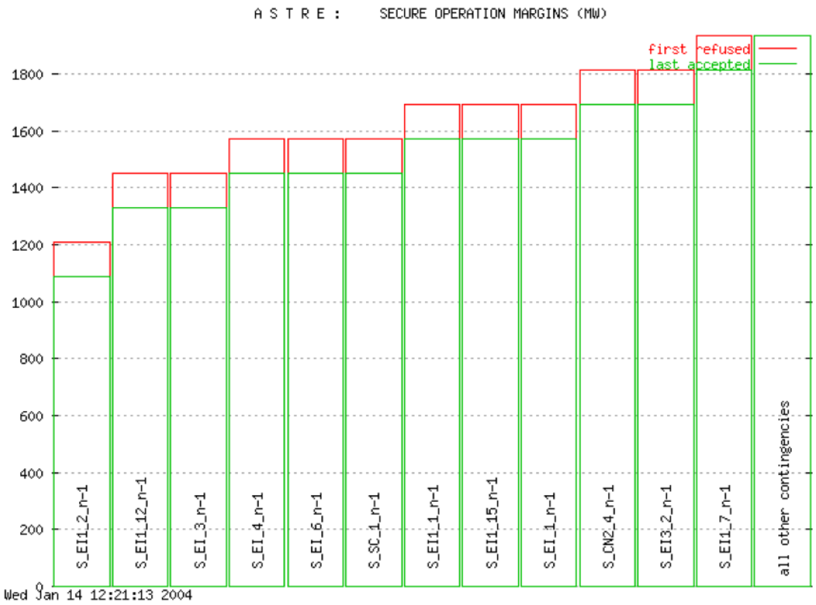


Fig. 8 Margins for Sim 5

When comparing the results of Sim 5 and Sim 1, it can be immediately noticed that the same contingencies have smaller margins in Sim 5. This means that the external stress is more critical than the uniform one. However, there is one contingency that has a very small margin (923 MW) in case of uniform stress, while in Sim 5 it is not even in the list of the most severe contingencies. This contingency is S_CS3_1_n-1, i.e. the loss of the line connecting Brindisi and Bari in the South of Italy. This is due to the fact that this contingency is located in the South of Italy, while the interconnection with neighboring countries is up North. Therefore, an external stress resulting in an increased import affects mainly the North of Italy and the lines going from North to South. On the other hand, a uniform stress affects in a "distributed" way the whole nation, and thus also the zone of Brindisi, that is weak.

As for voltage profiles, there is no big difference between Sim 1 and Sim 5: as Fig. 9 shows (if compared with Fig. 4b) contingency with wide effects in case of uniform stress has again wide effects in case of external stress.

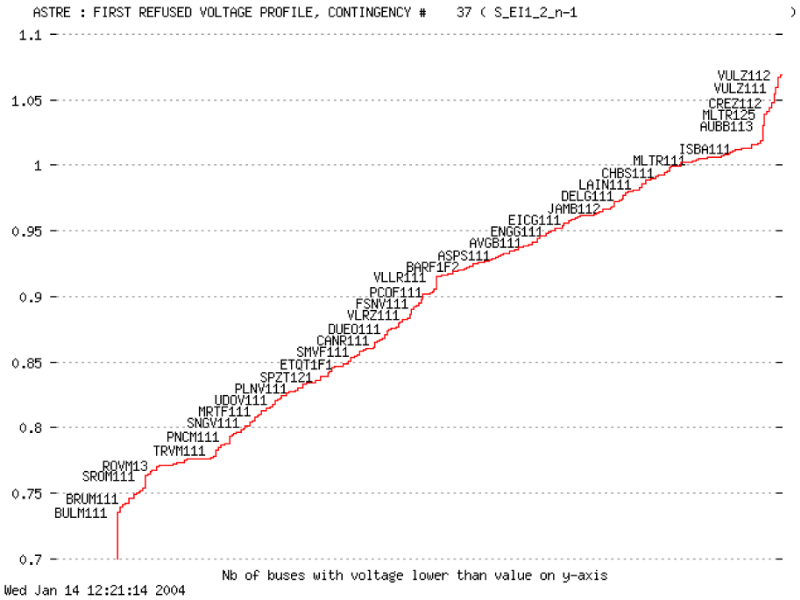


Fig. 9 Voltage profile for contingency S_EI1_2_n-1 (Sim5)

Again, since no margin is lower than 1,000 MW, there is no need for any load shedding.

4) Sim8 (External Stress, set_2_n-2):

The last simulation consists in determining the SOL with respect to the external stress and the set of n-2 generation loss contingencies. Fig. 10 collects the simulation results.

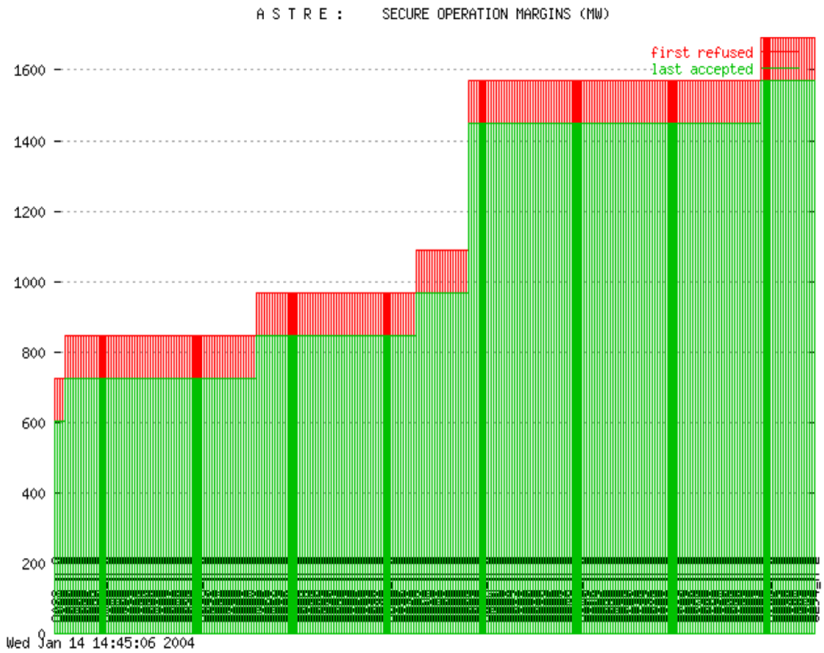


Fig. 10 Margins for Sim8

Also this simulation shows that the external stress produces smaller margins than the uniform stress for the same set of contingencies. In particular, set_2_n-2, i.e. the set made up of double generator loss contingencies, produces a lot of margins smaller than 1,000 MW. A load shedding action is thus needed for all these cases. The results of the load shedding analysis are presented in table II.

TABLE II LOAD SHEDDING RESULTS FOR SIM8

Contingency	Margin [MW]	Shedding Amount	
		[MW]	[MVAR]
G028_n-2	604	16.4	30.1
G011_n-2	604	150.4	24.3
G188_n-2	604	150.4	24.3
G189_n-2	604	164.1	30.1
G031_n-2	725	162.1	48.7
G115_n-2	725	127.0	42.8
G052_n-2	725	152.3	47.1
G195_n-2	725	957.0	14.4
G006_n-2	725	189.5	52.1
G201_n-2	725	113.3	18.9
G065_n-2	725	127.0	42.8
G222_n-2	725	130.9	43.4
G194_n-2	725	138.7	41.2
G245_n-2	725	142.6	45.4
G239_n-2	725	148.4	46.4
G193_n-2	725	140.6	23.2
G035_n-2	725	146.5	46.1
G022_n-2	725	210.9	54.3
G018_n-2	725	193.4	52.5
G106_n-2	725	175.8	50.7
G203_n-2	725	103.5	16.4
G105_n-2	725	168.0	49.7
G039_n-2	725	168.0	49.7
G103_n-2	725	189.5	52.1

Anyway, in this case it is possible to see that, even when losing simultaneously two large generating units, a limited load shedding (almost always smaller than 200 MW) is enough to preserve system stability.

IV. CONCLUSIONS

This paper has shown an application of the VSA approach adopted by the OMASES platform to a real power system operating scenario drawn from the Italian case. Valuable information was provided both in terms of system diagnosis (i.e. secure operation limits, voltage evolutions, voltage distributions, reactive reserves, etc.) and of support in decision making (i.e. suggestion of appropriate load shedding counteractions). The Quasi-Steady State Simulation, the calculation core of OMASES VSA tool based on a time-scale decomposition method, allows a dramatic increase in computational efficiency so that it is possible to handle thousands of contingencies on a realistic power system in less than 5 minutes: this makes it suitable for on-line VSA sessions within an EMS environment. As a matter of fact, the OMASES was interfaced with the EMS of the Italian and of the Hellenic TSOs. In particular, the VSA of OMASES is used for on-line voltage security assessment, moreover it was used to perform post-mortem analysis of blackouts and to evaluate the effectiveness of possible countermeasures. The present work has shown an example of offline application of the OMASES VSA approach (study mode).

The analysis, referred to a peak operating condition of a past model of the Italian network, proved that the system was compliant with the n-1 security criterion. The margins are lower in case of line losses than in case of generator contingencies: this happens because many lines are heavily loaded, especially the interconnection lines and the lines carrying energy from North to South.

As for n-2 contingencies, some have no margin, which means that the system is not always operated in n-2 security. Anyway, appropriate counteractions, such as load shedding, are enough to restore sufficient security margins.

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