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EXPERIENCE GAINED BY THE APPLICATION OF A REAL-TIME VOLTAGE SECURITY ASSESSMENT METHOD AT THE HELLENIC TRANSMISSION SYSTEM OPERATOR

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SUMMARY

Voltage instability is widely recognized as a significant threat of power system blackout. As far as real-time operation is concerned, there is a need for appropriate tools to identify dangerous contingencies and assess security margins. The Hellenic Interconnected System presents a structural geographical imbalance between the main generation site and the main load center. This imbalance leads to bulk power transfers over long distances leading to voltage stability problems in areas of the southern system during heavy load conditions. In order to improve the operational practices, a real-time Voltage Security Assessment (VSA) tool has been installed at the National Control Center of the Hellenic Transmission System Operator (HTSO). The scope of VSA is the analysis of the impact of significant contingencies and the determination of security margins in terms of power transfers or power consumption in load areas. The computations performed within the VSA tool are based on a Quasi-Steady-State simulation, a fast time-domain method well suited to the analysis of long-term voltage stability phenomena. VSA is performed on the current system state, provided by the Energy Management System (EMS) state estimator. The VSA application incorporates functions for filtering the contingencies, determining secure operation limits, and deriving post-contingency PV curves for the identified dangerous contingencies. This paper is a description of the experience and the added value gained by the application of the real-time VSA, in parallel with the existing EMS, at the control center of HTSO.

KEYWORDS

Voltage Stability, Voltage Security Assessment, Contingency Analysis, Quasi Steady-State Simulation, Secure Operation Limits, Loadability Limits, Energy Management System, Power Transmission.

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1. INTRODUCTION

Voltage instability is recognized as a significant threat of power system blackout [1,2]. As far as real-time operation is concerned, there is a need for appropriate on-line tools to identify dangerous contingencies, assess security margins and suggest corrective actions [3,4]. Over the last decade, efforts have been directed towards developing VSA methods compatible with the requirements of real-time applications, such as computational speed, easy data maintenance and appropriate man-machine interface for a control room.

The Hellenic Interconnected System (that covers the mainland and some islands of Greece) presents a structural geographical imbalance between the main generation site and the main load center. The largest amount of power is generated at the Northwest of the country by lignite-fired plants while the main consumption center is at the South including the Metropolitan area of Athens. This imbalance leads to bulk power transfers on long distances that may cause voltage stability problems in the areas of Peloponnese, Athens and Central Greece during heavy load conditions. The Hellenic power system has experienced a voltage instability incident in July of 1996 [5] and a blackout of the southern part of the system, due to voltage collapse, in July of 2004 [6]. The countermeasures undertaken to improve voltage stability were in two directions: transmission system reinforcement and improved operational practices. At a later stage, the installation of new generation plants in the South (during the next few years) is expected to further improve the situation.

In order to improve the operational practices, a real-time VSA tool has been installed at the National Control Center of HTSO, the independent transmission system operator responsible for the operation, control and security of the interconnected power system of Greece. This VSA tool has been developed within the framework of the OMASES project, sponsored by the European Union [7]. It was in on operation until June of 2003 when the project ended. During Fall of 2004, the VSA part of the project has been reactivated in order to implement user recommended modifications and use it as a real-time and study tool at the control center.

2. VOLTAGE SECURITY ANALYSIS METHOD

The heart of all computations performed within the VSA tool is Quasi Steady-State (QSS) simulation, a fast time-domain method well suited to the analysis of long-term voltage stability phenomena [2,8]. The essence of this method is that faster phenomena are represented by their equilibrium conditions instead of their full dynamics. This greatly reduces the complexity of the resulting model and hence provides the computational efficiency required for on-line application. Also, the amount of additional data required is moderate, so that data collection, validation and maintenance are kept simple and not time consuming. This method, which has been validated with respect to detailed time simulation, offers better accuracy and richer interpretations than simple methods based on load flow equations.

Loads are modelled at the Medium Voltage (MV) buses behind High Voltage (HV)-MV distribution transformers, in parallel with shunt compensation capacitors (if any). They are considered voltage dependent (both active and reactive) following an exponential model. Load power is restored mainly by the actions of the Load Tap Changers (LTCs) of the HV-MV transformers. QSS simulation reproduces the long-term dynamics of LTCs, OverExcitation Limiters (OELs), automatically switched shunt capacitors, secondary voltage control (if any), protection devices, etc. This simulation takes into account the (initial and subsequent) delays in between transformer tap changes, the delays before a synchronous machine is switched under constant field current, etc. Thus, QSS simulation can cover the system evolution from several minutes to one hour, or even more with a very moderate execution time.

Voltage security is analysed in terms of power transfers, referred to as *system stress*. A system stress is characterised by its direction, i.e. by the participation of each load active and reactive power to the overall load increase and that of each generator active power production to the overall generation adjustment. The stress is implemented by increasing the load and consequently the generation, leading to an increase of power transfers over weak corridors. VSA is performed at the current system state, provided by the EMS state estimator, and referred to as *base case*.

The main indices of voltage security considered for assessing the impact of contingencies are the Secure Operation Limits (SOLs). For a given direction of stress, the SOL corresponds to the most stressed operating point, such that the system can withstand the contingency of concern. This limit refers to the pre-contingency configuration of the system. In the SOL computation, the stressed system states are obtained from a pre-contingency load flow computation, while the effect of a contingency is assessed using QSS simulation, starting from the load flow solution. The pre-contingency stress assumes full load recovery. The SOLs are determined by a binary search [8].

Contingency filtering is an important step of a real-time security assessment application. In spite of the QSS simulation speed, it may take too long to simulate the system response to each contingency of a long list. Thus, an additional pre-filtering may be needed before the search is launched. This filtering consists of : (i) performing QSS simulation on a subset of contingencies labelled potentially harmful; (ii) identifying the latter as the contingencies that cause the load flow to diverge or some voltages to drop by more than a pre-specified threshold. To make the filtering as reliable as possible, the post-contingency load flow data must closely match the QSS model. To this purpose, the reactive power limits of the generators are updated with their active power and terminal voltages, while active power imbalances are distributed over them according to frequency control.

The contingencies with an SOL lower than a pre-defined value are examined further from another viewpoint, namely by determining how much the system can be stressed in its post-contingency state before reaching instability. To this purpose, VSA simulates the time response of the system to a ramp increase in demand and/or generation. All LTCs, OELs, etc. respond according to their time constants to this increase in demand. Similarly, the active power setpoints of generators are increased with time. The imbalances between load and generation due to losses and LTC deadband effects, are covered by the primary frequency control. The simulation results are used to demonstrate the system limits through local, regional and system-wide Power-Voltage (PV) curves, which are convenient, widely accepted graphical representations. These post-contingency PV curves demonstrate graphically the amount of load restoration achieved in each area and the whole system, following the contingency, as well as the corresponding transmission voltage of a typical bus.

3. IMPLEMENTATION AT THE HTSO CONTROL CENTER

3.1 VSA sequence and modes of operation

The VSA installed at the control center of HTSO relies on a WINDOWS server that hosts a relational database system, the VSA computation engine and the HTTP server. Client PCs illustrating the results of the analysis are connected to the server through a Local Area Network (LAN) under the TCP/IP protocol. The above server is separate from the mainframe computer, which runs under a VMS operating system and hosts the EMS platform and its hierarchical databases. The communication between the EMS and VSA computers is accomplished via FTP transfer of text files from EMS to VSA server (Figure 1).

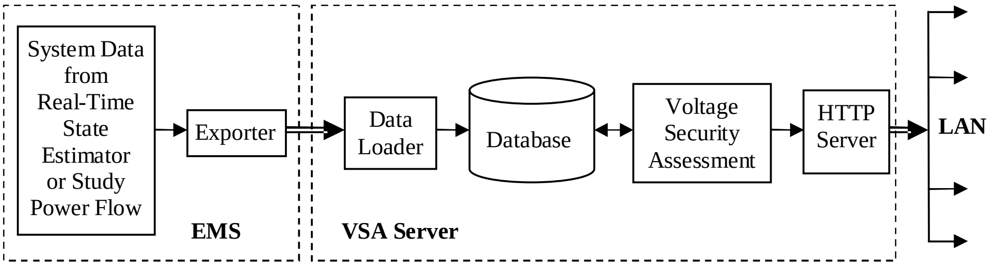

Figure 1. VSA sequence at the HTSO control center

An EMS data export process creates fourteen text files containing either the latest network solution computed by the real-time state estimator running periodically (every 10 minutes), or the solution of the study power flow which runs on user demand, depending on the operation mode. Each file is a description of power system components and corresponds to a table of the VSA database. These files are sent through FTP to a predefined entry directory of the VSA server. The entry directory is periodically scanned for the presence of new files sent by the EMS and, when available, the new files are uploaded to the relational database of the VSA server. The VSA function is informed of new data arrival, which triggers the computations. The VSA results are stored in the database and can be viewed through an HTTP server from the client PCs by using a browser.

The sequence described above can be run in three modes: real-time, study and expert. In real-time mode, the EMS feeds VSA with real-time state estimator solutions, as described above. The periodicity of VSA execution is currently set to 60 minutes, although the whole VSA execution takes from 5 to 10 minutes (on a Pentium IV PC) depending on the number of contingencies processed and the system state. The execution can also be initiated by an operator action if it is considered that the system state changes considerably between the periodic triggers. In study mode, the VSA execution is launched manually by the user. The data used are mainly saved snapshots retrieved from the historical database or from case studies used for system scheduling or planning. Finally, in expert mode, the experienced user can have access to diagnosis tools. For instance, in case of long-term voltage instability, a sensitivity analysis allows ranking the bus active and reactive power injections by decreasing order of their effectiveness in counteracting the instability, thereby pointing out where generation should be rescheduled or committed, or load shed.

3.2 Output Results

The following graphic outputs are available at the end of the VSA computations: security margins, voltage evolutions, voltage profiles and PV curves.

Margins in MW corresponding to the SOLs are displayed in a table format. Only contingencies with margins smaller than a maximum stress are shown. Voltage evolution plots show the post-contingency time evolution of a voltage magnitude in the marginally accepted and refused cases, respectively. Each curve relates to the bus experiencing the largest voltage drop due to the contingency. The time horizon of the QSS simulation is set to 1200 seconds. Voltage evolutions allow distinguishing between stability limits and low voltage limits. For instance, if the marginally refused simulation corresponds to a case where some voltages finally settle to a value a little below a specified threshold, then, the marginally refused case does not correspond to a voltage instability case. In this case the SOL should not be interpreted as a stability limit and the value of the margin is very dependent on the particular threshold chosen. On the other hand, when the marginally refused simulation shows voltages that drop well below the threshold without stabilizing to a low level, then this case corresponds to voltage instability and the SOL should be treated as a stability limit. A separate threshold is specified at the generator buses, so as to refuse a situation where the voltage of a field current-limited generator drops to an unacceptable value causing undervoltage protection to disconnect the generator thus initiating a cascade of events.

The geographical extent of the problems caused to the system by an unacceptable contingency is easily assessed from the voltage profiles obtained by taking a snapshot of the collapsing system at the marginally refused stress. It shows the number of buses that are below a voltage value. The affected area is identified from the names of typical buses.

Finally, for each contingency with a margin below some pre-defined threshold, a set of PV curves is produced, each relative to a particular area of the system. The abscissa shows the load power consumed in the area and the ordinate the voltage magnitude at a representative transmission bus of that area. Typical examples of the outputs described above are shown in the next chapter.

4. CHARACTERISTIC RESULTS FROM THE REAL-TIME OPERATION

In this chapter, results from two characteristic real-time operation cases are presented, together with their analysis and evaluation. The first case refers to a winter 2005 day and the second to the summer 2005 day with the yearly maximum load conditions.

4.1 Winter 2005 case

Peloponnese is a peninsula in southern Greece that is connected electrically to Athens area with 5 high voltage (150 kV) transmission lines through Korinth substation and to Western Greece through a pair of high voltage submarine cables in the area of Patra. The cables normally import power to Peloponnese from the Kastraki hydro generating station that consists of four units with a maximum capacity of 320 (4x80) MW. During high load conditions in Peloponnese, the usual practice is to split this station with two of its units connected to a bus supplying the cables and the other two units on a different bus interconnected to Western Greece. The objective is to control the current flow through the cables with the generation level at Kastraki.

Table 1 Voltage Security Margins (Feb.15th 2005, 18:30)

Contingency Name	MW
Line Megalopolis-Kalamata	0
Line Patra-Lapa	10
Unit GEN2 Kastraki	42
Unit GEN4 Kastraki	42

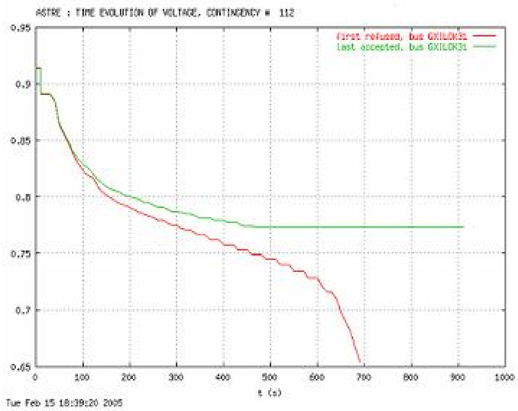

Figure 2. Voltage evolution after the loss of the line Patra-Lapa

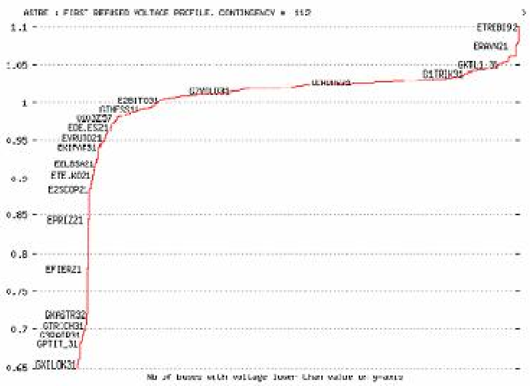

Figure 3. System voltage profile after the loss of the line Patra-Lapa.

On February 15th of 2005, real-time VSA showed a large difference in voltage security margins between the results of the 17:30 and 18:30 timestamps of the periodic execution. Although the security margins table of 17:30 did not include any contingency with a margin less than 1000 MW (with the exception of a few known outages with very local effect), the table of 18:30 included some contingencies at Kastraki and Peloponnese with zero or low margin, as shown in Table 1. No other indication of a problem (such as low voltages) appeared in the EMS SCADA or real-time state estimator results. An investigation on the validity of the above results showed that the reason was the opening of a Kastraki circuit breaker (bus coupler) at 17:45 that had separated the two units feeding Peloponnese for the afternoon high load period, as described above. The Peloponnese load increased between those timestamps from 620 to 706 MW. Also, in February 2005, a high voltage transmission line in Peloponnese from Patra to Korinth was open at the Xilokastro substation, somewhere in the middle of the distance, due to a transmission expansion project, resulting in a longer electrical way from Korinth to Xilokastro and western Peloponnese. Figure 2 illustrates the voltage evolution at the Xilokastro substation after the outage of the Patra-Lapa line for the marginally stable and unstable cases. The voltage collapse in the unstable case is evident. The corresponding system voltage profile (Figure 3) indicates that the area affected is close to Patra and extends to northern Peloponnese and the area of western Greece radially connected to Peloponnese.

The interpretation of these results led to a change in the way of operating the Kastraki station circuit breaker. Afterwards, when the station is electrically divided in two parts, three (instead of two) units feed Peloponnese through the submarine cables, providing a larger generation reserve to that area, and thus resulting in higher voltage security margins.

4.2 Summer 2005 case

Voltage security problems have appeared in the Greek interconnected system in its southern part mainly during the summer, when the load reaches its maximum and the power transfer from North to South is high. After the blackout of summer 2004, several transmission reinforcements were introduced in the system as described in the next section. Therefore, the summer of 2005 was a crucial period for testing the limits of the upgraded system and monitoring its voltage security margins in real-time. On August 3rd, 2005 at 13:55, maximum load occurred in the system with a value of 9642 MW. On that day (as well as the previous days) the real-time VSA results were closely monitored in order to spot contingencies resulting in voltage stability problems and indicate the nature of the problem and the available security margin. Based on that information, decisions could be made regarding system operation.

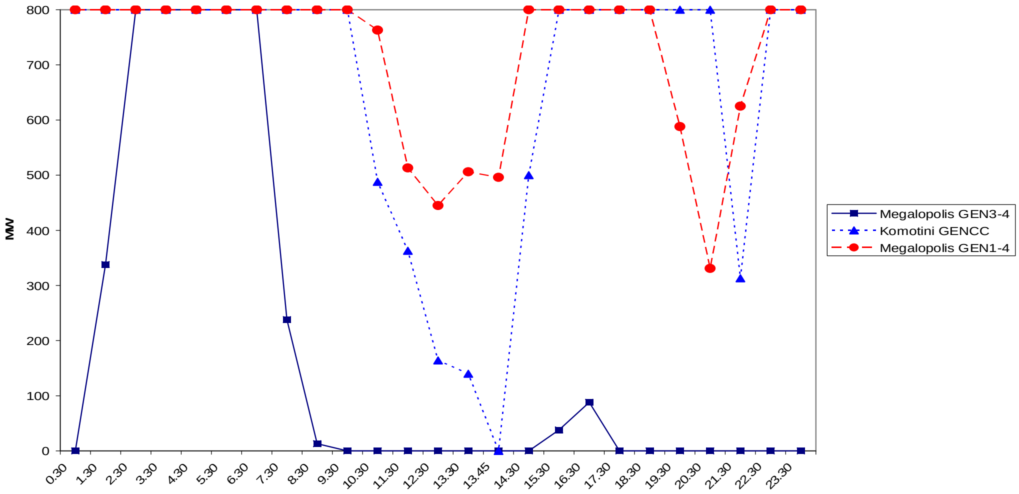

Figure 4. Evolution of voltage security margins on August 3rd, 2005.

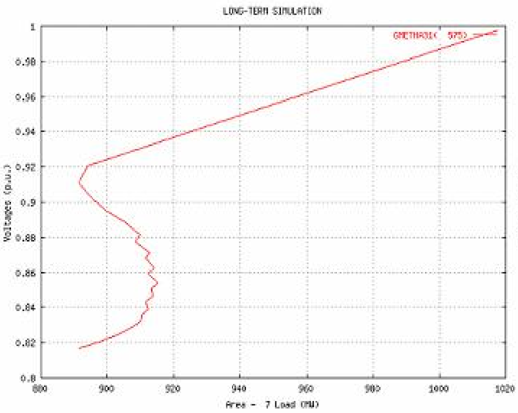

Figure 5. PV curve for the double unit outage at Megalopolis (units 3,4).

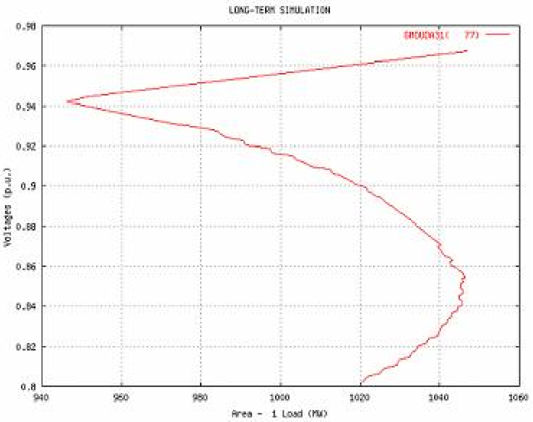

Figure 6. PV curve for the outage of combined cycle at Komotini.

All the contingencies that used to cause security problems in the Athens area (see next chapter), including those responsible for the July 2004 blackout, had in the Summer of 2005 an SOL larger than

500 MW. Figure 4 illustrates the evolution of the security margins, during that day, for the remaining three critical contingencies, namely generator outages in the power plants of Megalopolis (Peloponnese area) and Komotini (North-Eastern Greece). The value of 800 MW in the graph practically indicates margins larger or equal to 800, since this value is the maximum security margin considered in the analysis. The smallest margins appear during periods of high load conditions e.g. 12:00-15:00 and 20:00-22:00. The N-2 contingency that involves the loss of units 3 and 4 at Megalopolis had a zero security margin for several hours during that day. Peloponnese has become the most vulnerable part of the grid regarding voltage security and thus, several transmission projects are planned for this area in order to reinforce the system. The contingency at plant Komotini (loss of all three units of the combined-cycle) has also zero security margin for a timestamp very close to maximum load. Figures 5 and 6 show the regional PV curves for the contingencies at Megalopolis and Komotini (with zero margin close to maximum load). It can be seen that the Megalopolis contingency results in voltage instability in Peloponnese, since the load cannot be restored, while the Komotini contingency results in a marginal voltage instability in North-Eastern Greece. In general, operating conditions corresponding to such results, were considered satisfactory since no critical N-1 contingency appeared threatening the voltage stability of the system.

5. STUDY RESULTS ON THE IMPACT OF TRANSMISSION EXPANSION

The most severe incident of voltage instability in the Hellenic System occurred on July 12th, 2004, when the southern part of the country suffered a blackout lasting a few hours [6]. This incident happened just before the commissioning of some crucial transmission projects, which had been planned to reinforce the transmission system in the South as part of the preparation for the Athens 2004 Olympic Games in the second half of August. These reinforcements included the installation of additional autotransformers at EHV/HV substations in the metropolitan area of Athens and the adjacent area of Central Greece, the installation of mechanically switched capacitor banks at some crucial buses (totalling 400 MVAr) on both medium voltage (20-kV) and high voltage (150-kV) levels and some other reinforcements of the 150-kV network in the Athens region. Also, a gas turbine power plant (140 MW) was to be commissioned in the South under a special contract for voltage support.

A study using VSA (in study mode) was performed in Fall of 2004, in order to determine the impact of the above described transmission system reinforcements on voltage security margins. A case from real-time operation on July 9th was retrieved from the archives and used as base case. The peak load of that day was 8900 MW, while a 150 MW unit in the Lavrion plant close to Athens was out of service. Keeping the same load and generation profile, transmission reinforcements were added to the base case in order to examine their impact on voltage security. First, capacitors at MV buses were added, then capacitors at HV level and finally, three additional EHV/HV autotransformers. This way, three more cases have been created with gradual reinforcements of the system.

Table 2. Impact of successive network reinforcements on voltage security margins

Contingency Name	**Base Case**	**+ MV capacitors**	**+ HV capacitors**	**+ EHV/HV autotransformers**
LAVRION.CC3.GEN2	0	295	388	555
LAVRION.CC4	0	274	325	491
LAVRION.CC3	318	>650	>800	>826
LAVRION.GEN2	374	>650	>800	>826

Previous analyses had shown that the most severe contingencies involved the loss of generation in the area of Athens. In the results presented below, only these most severe contingencies are reported. The contingencies of interest refer to N-1 and N-2 outages as follows:

- loss of two units with a capacity of 470 MW of the Lavrion plant located near Athens (referred to as LAVRION.CC3.GEN2)
- loss of the combined cycle power plant in Lavrion with a capacity of 580 MW, consisting of 3 gas and one steam turbine (LAVRION.CC4)

- loss of the small combined cycle power plant in Lavrion with a capacity of 170 MW (LAVRION.CC3)
- loss of a steam turbine in Lavrion with a capacity of 300 MW (LAVRION.GEN2)

The SOLs relative to the above contingencies are shown in Table 2. Note that the first two contingencies have zero security margins in the base case. Comparing the values in the second and first column, one can see the considerable benefit of the capacitors at MV buses. These capacitors are very close to the reactive loads and their impact is much larger than those located at the HV buses (third column). The impact of the EHV/HV autotransformers is also important (fourth column). These transformers link the EHV system (where most of the generation is located) to the HV system (where most of the loads are connected) and their addition reduces the effective impedance between generation and load.

6. CONCLUSION

This paper presented a Voltage Security Assessment tool in operation at the control center of the Hellenic Transmission System Operator, in real-time and study environments. Specifically, it described the analysis methods used, the application of the tool within the existing control center EMS and some characteristic results from both real-time and study modes. The real-time application of VSA proved very useful during the daily operation of the system since it gives an updated indication to the operator, as the system changes with time, about possible voltage security threats to the system. The available tools indicate the nature of possible threats (voltage collapse or low voltages), their geographic extent, as well as the corresponding security margin in terms of acceptable load increase. This allows system operators to make decisions and take actions based on unbiased information. In study mode, VSA can be used as a tool for planning system transmission and generation expansion and assess the effect of reinforcements on voltage security.

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