INVESTIGATION OF PARAMETERS AFFECTING VOLTAGE SECURITY OF THE HELLENIC INTERCONNECTED SYSTEM

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Abstract – The Hellenic Interconnected System presents a structural geographical imbalance between generation sites and load centers. This imbalance leads to bulk power transfers on long electrical distances leading to voltage stability problems. In order to improve the operational practices aiming at improving the voltage security, an on-line Voltage Security Assessment tool has been installed at the National Control Center of the Hellenic Transmission System Operator that operates and controls the interconnected power system of Greece. This paper presents some indicative results obtained by the use of this tool. The analysis includes the investigation of the main parameters that affect the voltage stability of the system, such as the position of non-automatic taps of autotransformers, the network topology, and the spatial distribution of generation.

Keywords: Voltage stability, Voltage security, Contingency analysis, Security margins, Loadability limits, Optimal Power Flow.

1 INTRODUCTION

Voltage instability is widely 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 tools to identify dangerous contingencies, assess security margins and suggest corrective actions [3,4]. Over the last decade, efforts have been directed towards developing Voltage Security Assessment (VSA) methods compatible with the requirements of on-line applications (computational speed, data maintenance, significance of displayed results, etc.). Examples of such developments are given in [5], which describes the general practice and gives a sample of existing tools, while [6] presents techniques for the determination of stability limits.

The Hellenic Interconnected System (that covers mainland Greece and some adjacent islands) 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 while the main consumption center includes the Metropolitan area of Athens at the South. This imbalance leads to bulk power transfers on long distances leading to voltage stability problems in the southern areas of Peloponnese, Athens and Central Greece during heavy load conditions. The Hellenic power system has experienced a voltage instability incident in July 1996 [7] and a blackout of the southern part of the system, due to voltage collapse, in July 2004. Countermeasures undertaken to improve voltage stability include transmission system reinforcement and improved operational practices. Also, the installation of new generation plants in the South during the next few years is expected to improve the situation even more.

In order to improve the operational practices, an on-line VSA tool has been installed at the National Control Center (NCC) of Hellenic Transmission System Operator (HTSO). HTSO is an independent system operator responsible for the operation, control and security of the interconnected power system of Greece. This VSA tool has been developed by the National Technical University of Athens and the University of Liège within the framework of the OMASES project, sponsored by the European Union [8]. It was in on-line operation until June of 2003 when the project has ended. In Fall of 2004, VSA has been reactivated in order to implement user recommended modifications and use it as an on-line and study tool at the control center. VSA is fed with raw system data either from the real-time State Estimator or the study Power Flow program available at the NCC. 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 VSA application incorporates functions for filtering the contingencies, determining (pre-contingency) secure operation limits, and computing (post-contingency) loadability limits for the previously identified dangerous contingencies. A by-product of this last computation is a set of PV curves showing voltages at key buses versus regional or system load.

This paper presents some indicative results obtained from the VSA tool. The analysis includes the investigation of the main parameters that affect the voltage stability of the system with emphasis in the areas mentioned above, since voltage security problems that occur in other areas have only local impact and do not affect the overall security. The ratio of the 400 /150 kV autotransformers, the network topology, and the spatial distribution of generation are the main parameters under investigation.

In Section 2, the highlights of the VSA method are presented. A short description of the main characteristics of the Hellenic System is presented in Section 3, together with the transmission system reinforcements implemented in 2004. Finally, in Section 4 the cases that were analyzed by VSA are described together with their respective results, followed by the conclusions in Section 5.

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 [2,9]. 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. Moreover, the amount of additional data required is moderate, so that data collection, validation and maintenance is not a big issue. 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.

Under the QSS approximation, the short-term dynamics of a synchronous generator, its governor and its Automatic Voltage Regulator (AVR) are replaced by three nonlinear algebraic equations representing the generation saturation, the AVR steady-state gain and the speed droop. These nonlinear equations are solved at each time step, together with the network ones. Loads are modelled at the MV buses behind 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), protecting 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 a few hours with a very moderate execution time.

Voltage security is analysed in terms of power transfers, referred to as *system stress*. This stress is implemented by increasing the load and consequently the generation, leading to an increase of power transfers over weak corridors and/or by drawing on reactive power reserves. VSA is performed at the current system state, provided by the Energy Management System (EMS) state estimator, and referred to as *base case*. Two indices of voltage security have been considered for assessing the impact of contingencies, the *secure operation limit* (SOL) and the *loadability limit*.

For a given direction of stress, the *secure operation limit* corresponds to the most stressed operating point such that the system can withstand any contingency of a specified list. This limit refers to the current, 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 *binary search*. This simple and robust method consists of building smaller and smaller intervals [S_l S_u] of stress values such that S_l corresponds to an acceptable post-contingency evolution and S_u to an unacceptable one. At each step, the interval is divided in two equal parts; if the midpoint is found acceptable (resp. unacceptable) it is taken as the new lower (resp. upper) bound. The procedure is repeated until S_u - S_l is smaller than a specified tolerance. To make the function automatic, the binary search starts with $S_l = 0$ (corresponding to base case) and

$$S_u = \min (S_{max},\ f \,.\, S_N) \quad (1)$$

where S_{max} is the maximum stress of interest, S_N the maximum stress that can be reached in the absence of contingency and f is typically equal to 0.9. S_N is itself determined by binary search, considering an “empty” contingency.

A *loadability limit* indicates how much the system can be stressed before reaching instability. To this purpose, VSA does not resort to repeated power flows, but rather 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. To this purpose, the frequency deviation is computed at each time step of the QSS simulation. Loadability limits are computed in the base case configuration, as well as for a limited set of dangerous contingencies. These limits are referred to as *Post-Contingency Loadability limits* (PCLL). The contingencies are simulated over a specified time interval, before the ramp increase in demand and generation is applied. Besides power limits, the main outcome of such a simulation is a set of familiar PV curves. The SOL determination is performed first; then the PCLLs and PV curves are computed for the contingencies with the lowest margins.

It is clear that SOLs and PCLLs give different information and call for different interpretations. SOL is better suited to quantify the “distance to insecurity” in terms of total system load. Along the pre-contingency stress we have normal operating points similar to those that operators are used to observe. On the other hand, the trajectory leading to a PCLL does not consist of "normal" operating points and the PCLL is not to be handled as a quantitative measure. Rather, it is valuable to demonstrate the system limits through local, regional, system-wide 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 in the whole system following the contingency (as well as the corresponding transmission voltage), and are thus providing useful information, complementary to SOLs.

VSA function can be run in three modes: *real-time*, *study* and *expert*. In *real-time mode*, the EMS feeds VSA with network state estimator solutions, as described above. The execution of the VSA application is periodic and triggered automatically by the data transfer from the EMS. The periodicity of VSA execution is in the order of every 30 minutes. The execution can also be initiated by an operator action if it is considered that the system state changes considerably between the periodic triggers. The whole VSA cycle takes 3 to 4 minutes on the average (on a Pentium IV PC). Real-time mode is used for the evaluation of the voltage security of the current system in operation.

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 the current system state in operation. A network solution stemming from a power flow program (saved cases) or the EMS state estimator is thus retrieved as initial condition in this mode of operation. A solution from the real-time state estimator is used as a basis for the voltage security evaluation of short-term operation measures, while a saved solution from a power flow is used as a basis for planning studies.

Finally, in *expert mode*, the experienced user can have access to diagnosis tools, such as sensitivity and eigenvector analysis of Jacobian matrices. In case of long-term voltage instability, an analysis of the long-term Jacobian 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. When a singularity of the QSS time evolution has been met, corresponding to the loss of a short-term equilibrium, the short-term Jacobian is analysed to find which generators are mostly responsible for the loss of synchronism.

3 NETWORK REINFORCEMENT OF THE HELLENIC INTERCONNECTED SYSTEM

The Hellenic interconnected system includes the generation and transmission systems of mainland Greece and some adjacent islands. The main production center is located in the northwest part of the country, close to the lignite mines, which is the basic fuel source, while the main center of consumption lays in the southern part including the metropolitan area of Athens. The installed generation capacity of the interconnected system is about 10700 MW with 48% lignite, 29% hydro, 14% natural gas, 7% oil and 2% renewable. The generation capacity at the southern part of the country is about 2550 MW, installed mainly at the power plants of LAVRION, AG. GEORGIOS (both near Athens) and MEGALOPOLIS (in Peloponnese).

The transmission system operates at the levels of 400, 150 and (very limited) 66 kV. There are 5 AC interconnection lines with the neighbouring countries in the north (with a net transfer capacity of 600 MW) and a DC interconnection with Italy via a submarine cable (with a maximum capacity of 500 MW).

As already mentioned, the geographical imbalance between generation and consumption leads to bulk transmission in the North-South direction. This imbalance is continuously increased due to the high increase of the yearly peak loads mainly in the south; such peaks occur during the summer period and they are mainly due to air-conditioning devices. The delays in the implementation of planned transmission projects (mainly due to public protest) makes the situation even worse. Thus occasionally the Hellenic system faces critical operational conditions regarding voltage stability. Such incidents have been experienced in the past [7, 9]. The most severe one occurred on July 12th, 2004, when the southern part of the country suffered a blackout lasting for two hours. This incident happened just before the commissioning of some crucial transmission projects, which had been planned to reinforce the transmission system in order to improve voltage stability and increase the transfer capacity from North to South. 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 substations (totally 400 MVAr) on both medium voltage and 150 kV buses and the reinforcement of the 150 kV network in Athens region. These transmission projects had been considered necessary since Athens was the host of the 2004 Summer Olympic Games. The deadline for the commissioning of these projects was the 15th of July. Also, a crash program was tendered by HTSO to install gas turbines (140 MW) in the south at the new Thermal Power Plant (TPP) of Heron, under a special contract, to be used during peaks for voltage support. The official commissioning date of this plant was the end of June, but the project was delayed for about a month due to licensing problems.

4 VOLTAGE SECURITY ANALYSIS OF THE HELLENIC INTERCONNECTED SYSTEM

4.1 Test cases description

The indicative analysis presented in this section aims at investigating the influence of the main parameters that affect the voltage stability of the system with emphasis in the southern part (Athens area, Central Greece and Peloponnese). The analysis is performed for two load levels, namely 8884 MW and 9526 MW of total system load (including transmission losses). The former represents a high system load that occurred on July 9th, 2004 and resulted in low voltages in the south; the initial system data have been retrieved from the EMS real-time state estimator. The latter refers to the reinforced transmission network and has been constructed starting from a real snapshot (of September 2nd, 2004) by applying a uniform increase in total system load.

The main differences between the topologies examined (i.e. July 9th and September 2nd) are:

- the installation of 3 autotransformers at EHV/HV substations (two in Athens area) in parallel to the existing ones
- the operation of excess capacitors of a total capacity of 220 MVAr (100 MVAr of which at 150 kV side of EHV/HV substations in the Athens region)
- the operation of a crucial 150-kV substation in the Athens region feeding about 250 MW
- the commissioning of a new underground cable in the Athens region.

Also, it must be noted that the network in the Athens region on July 9th was in a transient period (due to the construction) and it was not operated in its usual configuration.

Previous VSA analyses have shown that the most severe contingencies involve the loss of generation in the Athens area and Peloponnese. In the results presented below, only the most severe contingencies relating to loss of generation in the south are reported, since all other contingencies with small margins have only local impact and do not affect the overall security. The contingencies of interest refer to N-1 and N-2 cases as follows:

- loss of two generators (N-2) with a capacity of 470 MW feeding the 150-kV and 400-kV buses of the TPP Lavrion located near Athens (referred as LAVRION.CC3.GEN2)
- loss of the combined cycle power plant at TPP Lavrion with a capacity of 580 MW, consisting of 3 gas and one steam turbine. This is also considered an N-2 contingency (LAVRION.CC4)
- loss of one smaller combined cycle power plant at TPP Lavrion with a capacity of 170 MW, feeding a 150-kV bus. This is considered as a N-1 case (LAVRION.CC3)
- loss of a steam turbine at TPP Lavrion with a capacity of 300 MW, feeding a 400-kV bus (LAVRION.GEN2)
- loss of a generator at TPP Megalopolis in Peloponnese with a capacity of 300 MW (MEGALOPOLIS .GEN4)
- loss of another generator at TPP Megalopolis with the same capacity (MEGALOPOLIS.GEN3).

The investigation presented below refers to the following parameters that affect voltage security:

- system topology, in order to depict the influence of the planned transmission reinforcements
- installation of additional generation in the south
- improved operational practices as recommended by the Optimal Power Flow (OPF) application of EMS.

These recommendations refer to the position of the taps of the autotransformers at the EHV/HV substations and the distribution of reactive power production among the generators.

Load shedding schemes and Special Protection Systems (SPS) were not considered in this study, which deals only with preventive voltage stability analysis and not with corrective (emergency) controls.

Six different study cases have been created taking into consideration the above parameters. The first three use as base case the snapshot of 8884 MW while the other three use as base the study case with higher load at 9526 MW. The description of these cases and the results of the respective voltage security analyses are presented in the following subsections.

4.2 Real-time case of July 9th, 2004

On July 9th, 2004 low voltages occurred in the area of Athens and the adjacent area of Central Greece. The voltage levels were as low as 0.935 pu at the 400-kV level and 0.913 pu at 150 kV, with a normal low operation limit of 0.95 pu. The peak load of that day was 8884 MW at 13:20. A unit with a capacity of 150MW at TPP Lavrion was out of operation while the new power plant of Heron (mentioned in Section 3) had not been commissioned by that time. Additionally, the transmission reinforcement program was not complete leaving the network in a transient operating state. Only two of the new autotransformers were in place in two EHV/HV substations in Central Greece and some of the planned capacitors.

contingency	case1	case2	case3
LAVRION.CC3.GEN2	0	77	555
LAVRION.CC4	0	77	491
LAVRION.CC3	318	385	>826
LAVRION.GEN2	374	461	>826
MEGALOPOLIS.GEN4	261	385	529
MEGALOPOLIS.GEN3	>598	>615	>826

Table 1: Secure Operation Limits in cases 1-3

The voltage security analysis of this case (named case1) yields the SOLs shown in Table 1. The applied stress is an increase in the total system load. The contingencies referred to in the table have been described in the previous section. The N-2 contingencies (LAVRION.CC3.GEN2, LAVRION.CC4) have zero security margin, while the margin of the most severe N-1 contingency (MEGALOPOLIS.GEN4) is 261 MW, resulting in a voltage stability limit for the total system load at the level of 9145 MW (=8884+261). The PV curves for this case are given in Figs. 1 and 2. In Fig. 1 the curves refer to the N (no contingency) state of the system while in Fig. 2 the curves refer to the most severe N-2 contingency LAVRION.CC4. The load power is considered as the sum of consumer loads and power plant auxiliaries. The voltage is that of a crucial 150 kV bus in the Athens area.

As seen in Fig. 2, after the N-2 contingency the voltage drops abruptly to 0.95 per unit, while due to the voltage sensitivity of the loads the total active power consumed is reduced to about 8800 MW. After this point load starts to be restored due to distribution voltage adjustment by LTCs, as well as due to the simulated load demand ramp. However, due to LTCs reaching their regulating range limits and/or to maximum power transfer limitations, the load cannot be fully restored at its pre-contingency level. A continuation of load ramping up under this conditions may result in a voltage collapse.

The described case was used as a basis for investigating the effect of operational changes recommended by the OPF and the benefit of the planned transmission reinforcements. The results of this investigation are presented in the next two sections.

4.3 *Effect of OPF recommendations*

An OPF study has been done based on the real-time state estimator results in order to improve the voltage profile of the previous real-time case. The selected control variables for OPF are the reactive generations of power plants and the autotransformer ratios at the EHV/HV substations in the southern part of the system [11]. The selected control generators behave as PQ-bus generators while the rest as PV-bus ones. The range of reactive generation of a unit is given by its capability curve and its current operating point. The taps are located on the HV (150-kV) side of the autotransformers and the tap positions range from 1 to 19. By moving the tap from position 1 to position 19 the voltage decreases from 1.2 to 0.9 pu and vice-versa.

The suggested control actions consist of moving the EHV/HV autotransformer taps in the areas of Athens and Central Greece at lower positions in order to improve the voltage profile at the 150-kV load buses, as well as re-dispatching reactive power among units in the area of Athens and neighboring Peloponnese. The new positions resulted in an improved voltage profile, with all voltages at the HV level in the regions of Athens and Central Greece within their normal operating limits. The suggested controls also result in a reduction of total reactive power system losses by 26%. This reduction is achieved by lower transmission line currents due to higher bus voltages. The lower reactive losses allow a reduction of total reactive power generation by 7%.

The SOLs of this case (named case2) are given in Table 1. There is an increase in the margins of the N-2 contingencies from 0 to 77 MW, and also an increase in the margin for the most severe N-1 contingency from 261 to 385 MW (a 48% increase), resulting in a voltage stability limit of 9269 MW for the total system load in this improved state. The PV curves for this case are shown in Figs 1 and 2 together with those of case1. In Fig. 2 a load reduction and voltage increase is observed in case2 before the application of the disturbance, because of dynamic system response to the changes made in the operating point. The critical points of the curves for case2 are at higher load and voltage levels than those of case1, showing improved loadability limits.

4.4 *Effect of network reinforcements*

A study has been performed in order to see how the situation of case1 would improve if all the planned network reinforcements described in Section 3 were effective (except for TPP Heron, which operates under a special contract for demand peaks). This new case (named case3) has been constructed using as basis the snapshot of Sept. 2nd, 2004 (that includes the complete reinforced network) and applying a uniform load increase in each area, so as to match the 8884 MW load of case1. It also the same generation scheme as case1. A comparison of case3 (network with reinforcements) with case1 (network without reinforcements) shows for case3 a much better voltage profile (with all voltages well above their lower operating limits), a reduction of the total reactive power losses by 59% and a reduction of the total reactive power generation by 25%.

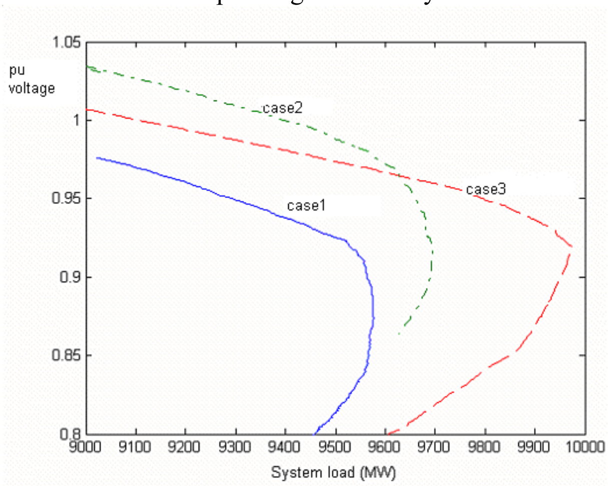

Figure 1: PV curves for no contingency

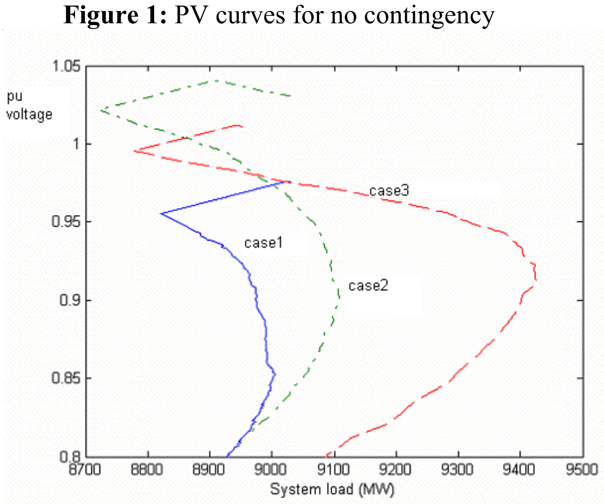

Figure 2: PV curves for contingency LAVRION.CC4

The SOLs for this case are also shown in Table 1. The margins for the N-2 contingencies increase from zero (case1) to values in the order of 500 MW. The margin for the most severe N-1 contingency increases from 261 to 529 MW, a 102% increase. The PV curves for this case are given in Figs 1 and 2. The critical point of the curves of case3 is at a higher load and voltage levels than those of case1 and case2, showing substantially improved loadability limits for the reinforced network.

4.5 VSA at higher system load

This section presents the analysis of a study case built up by ramping up the load and generation profiles during the peak hour of September 2nd to detect the influence of the new peaking gas turbines installed in the southern part of the system and assess voltage security margins of the new reinforced system under heavier loading conditions. The total system load has been scaled to 9526 MW (which represents the expected peak load for 2004) and all available generators have been assumed to be in operation; all the transmission system reinforcements have been assumed to be effective as well. Three variants of this case are examined:

- V1 assumes that the peaking gas turbines (140 MW) of TPP Heron are out of operation
- V2 assumes that the peaking gas turbines (140 MW) of TPP Heron are in operation
- V3 is as V2 with additional OPF recommendations implemented.

The power flow results for V1 and V2 show low voltages in the areas of north-eastern Greece and the area of Patras in the Peloponnese, while the voltages in the Athens area and Central Greece are well above their lower operation limits. An OPF study has been done in order to improve the voltage profile in those areas . The recommendations include tap position changes in two EHV/HV substations in Central-Eastern Macedonia and reactive power re-dispatch of power plants in all the affected areas. As a result, all voltages in the areas of concern return inside their normal operating limits. This optimized case constitutes variant V3.

contingency	V1	V2	V3
LAVRION.CC3.GEN2	374	475	673
LAVRION.CC4	280	396	606
LAVRION.CC3	>598	>633	>861
LAVRION.GEN2	579	>633	>861
MEGALOPOLIS.GEN4	504	593	807
MEGALOPOLIS.GEN3	504	593	821

Table 2 : Secure Operating Limits of variants 1-3

Table 2 summarizes the SOLs for the most harmful contingencies. Obviously, the secure margins are increased by 100 MW approximately, due to the addition of the generation of the peaking gas turbines (comparison of V2 versus V1). Comparison of V2 and V3 clearly shows, once more, the importance of optimizing autotransformers tap positions since they influence significantly the security margins. The SOL of the most severe contingency of V3 is at 606 MW, resulting in a voltage stability limit for the total system load, for this optimized case, at the level of 10115 MW.

5 CONCLUSIONS

This paper presented a voltage stability analysis of some indicative cases of the Hellenic Interconnected System. An on-line and study VSA tool installed at the NCC of HTSO has been used. The analysis aimed at investigating the impact of the main factors affecting voltage stability, in the light of the recent blackout, which occurred on July 12th, 2004. These parameters refer to system topology (i.e. new transmission elements and compensation devices), new generation in the weak (southern) areas and reactive power management.

The conclusions reached by the analysis of various cases can be summarized as follows:

- the analysis of the snapshot of July 9th, 2004 showed the danger of a voltage collapse in the south in case of excessive loss of local generation, which actually happened on the next working day of July 12th and led to the blackout;
- although an optimized reactive power management (as recommended by OPF) could increase the security margins of that day, this was probably not enough to prevent the black-out;
- the black-out could have been prevented if all the planned transmission and generation enhancements had been put in operation;
- the optimization of the non automatic tap ratios of the autotransformers in EHV/HV substations is a very effective measure for efficient reactive power management in order to increase voltage security margins. These optimal taps should be evaluated (using OPF) and reset periodically to reflect the current system topology, generation and load level;
- an on-line VSA tool at the control center allows system operators to make decisions and take actions (e.g. for load shedding) based on unbiased estimation;
- the VSA tool can be also used efficiently for planning studies.

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