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# At the Edge of Voltage Collapse in Slovenian Power System After Outage of NPP Krško and 400 kV Node Tumbri

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## SUMMARY

A major disturbance that resulted in the tripping of the 400 kV line Tumbri (HR) – Hévíz (H) and the entire 400 kV node Tumbri in the Croatian system occurred on 27 August 2003 and almost led to a voltage collapse in that area. The disturbance was initiated by an accidental outage of a generator at NPP Krško (SLO) due to a human error during regular maintenance work. Its further development was the consequence of a hidden fault of the numeric protection at the 400 kV switchyard Tumbri. In the specific system operating conditions (network configuration and generator scheduling) at that moment, the systems of Slovenia and Austria in the central part of the UCTE system were brought near voltage collapse. At the same time the operational security level of the power systems of Croatia and BiH, then at the perimeter of the UCTE system, was also decreased.

The sequence of events is described and discussed in the paper. Recordings of frequency and active power in representative transmission lines, taken at NDC Zagreb, are also given. A simulation analysis was performed first for the real disturbance scenario and then for the hypothetical scenario in which there was no failure of the protection at Tumbri substation and consequently the 400 kV node Tumbri would have remained in operation. The simulations showed that the loss of a NPP Krško generator would have only a local impact and would be barely noticeable at the UCTE level had the 400 kV node Tumbri remained in operation. Simulation results are in accordance with information obtained from the Slovenian power system where severely depressed voltages were recorded, particularly in the area around NPP Krško. It was also observed that the Slovenian system was acting as a reactive power sink while active power was flowing in the opposite direction, i.e. towards Croatia.

Assessment of Croatian system security during the disturbance with respect to voltage stability, frequency and angle stability and congestion criteria was done on the basis of measurements and simulation results. The conclusion was that Croatian system security with respect to all the above mentioned criteria was preserved but it must be stressed that the initial system operating conditions were rather favorable from the stability point of view.

## KEYWORDS

Power system dynamics, power system security, outage, voltage and angle stability, relay protection

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## 1. INTRODUCTION

Major disturbances in power systems have serious technical and economic consequences. The analysis of actual disturbances point to technical and/or organizational weaknesses in the system and makes it possible to take measures to remove the observed deficiencies. At the same time, the analysis of how the system behaves during the disturbance enhances the understanding of its characteristics. This is important for predicting possible states and scenarios in which system security is jeopardized.

An especially tricky situation occurs when disturbances occur at such points or with such an intensity that they significantly affect the operation of neighboring systems or even a broader area. The analysis of such events requires close cooperation among operators, including exchange of available information, records and measurements. Large-scale disturbances also mean real primary verification of system protection actions, from local plant level to special protective schemes at system level.

The present paper describes an event which included the outage of a major power plant and several interconnection lines, affecting a number of power systems (principally Slovenia (SLO), Croatia (HR), Austria (A) and Hungary (H)).

## 2. POWER SYSTEM CONFIGURATION AND STEADY STATE

The configuration of Croatia’s 220 and 400 kV transmission network and its interconnections with neighboring systems is shown in Figure 1. The nuclear power plant Krško (NPP Krško), a generating facility located near the Croatian-Slovenian border, is used jointly by the Croatian and Slovenian utilities in the ratio 50:50. The 400 kV node Tumbri and/or the 400/110 kV Tumbri substation is a key point for the supply of the local power system of the city of Zagreb (HR) and its surroundings. Incidentally, this fact was actually confirmed by an event that took place on January 22, 2003. On that day, a failure of one 110 kV circuit breaker in Tumbri substation and action of bus protection led to the outage of the 110 kV node Tumbri and subsequent blackout in the city of Zagreb and north-western Croatia.

The interconnections between the Hungarian and Croatian systems, a 400 kV double-circuit line Tumbri (HR) – Hévíz (H), built and operating at that time as a single circuit, is significant for the security of the Croatian power system and it establishes an important electricity transit route, Hévíz (H) – Tumbri (HR) – Melina (HR) – Divača (SLO) – Italy (I), from the northeast to the southwest of the UCTE interconnected system. Consequently, the availability and any disturbance of this interconnection is of special interest for the UCTE interconnected system and for the Croatian system as its part.

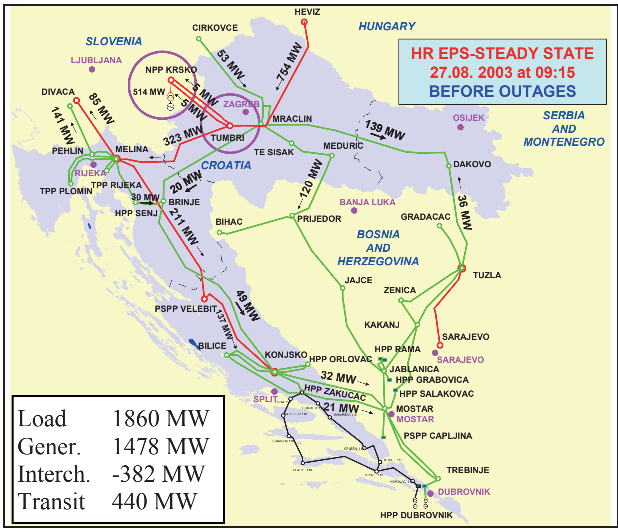



Figure 1 Configuration and power flows in HR system before outage of NPP Krško and 400 kV nodeTumbri

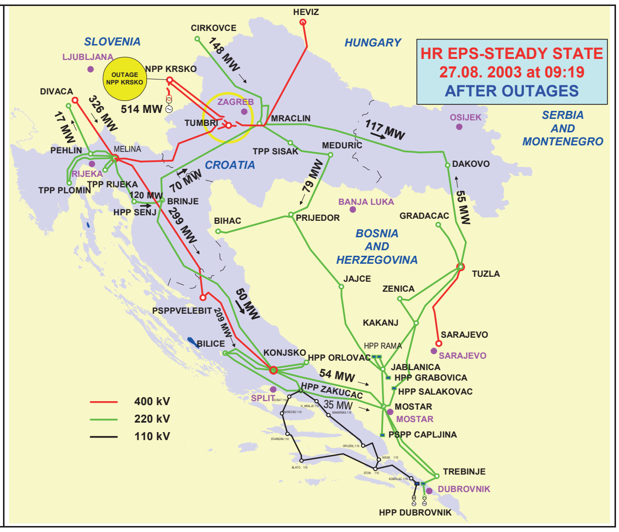



Figure 2 Configuration and power flows in HR system after outage of NPP Krško and 400 kV node Tumbri

The event considered occurred on August 27, 2003 at 9:15:10.008. The transmission networks of Croatia and BiH and their mutual interconnections at that time (Figure 1) were not built at the today level. In the Croatian system the 400 kV Žerjavinec and Ernestinovo substations did not exist then so that the eastern part of Croatia was connected to the Zagreb area at the 220 kV level (Figure 1, the 220 kV line Mraclin – Đakovo). As mentioned above, in operation was only one circuit of the present-day double circuit 400 kV interconnection TS Žerjavinec – TS Hévíz, introduced into Tumbri substation.

Active power before the event was flowing from the north-eastern toward south-eastern part of the UCTE system through Hungary, Austria, Croatia and Slovenia, with the concentration of demand being in Slovenia, Italy, Croatia and BiH. Interestingly, due to relatively low voltages in Austria (southern part) and Slovenia, reactive power flows had the opposite direction, i.e. from Italy and Croatia through Slovenia to the southern part of Austria. It should be noted that active power flow from Hévíz to Tumbri (Figure 1) immediately before the event was 754 MW.

Following the outage of a NPP Krško unit and subsequent tripping of the 400 kV node Tumbri, active power began to flow through Austria, Germany and Italy toward Slovenia, Croatia and BiH where power imbalance further increased due to the outage of the NPP Krško unit. Voltage conditions deteriorated in Austria and Slovenia especially after the connections between Austria and the Czech Republic were switched off. These connections were in fact switched off by the first action of the system protection ("Sollbruchstelle") in the Austrian system. The area around the 400 kV node Krško was especially critical and on the brink of voltage collapse. The results of simulation of system dynamics undoubtedly show and confirm that, as illustrated below. Reactive power continued to flow from Italy and Croatia through Slovenia toward the southern part of Austria, now in greater amounts.

Active power flows on the lines before (09:15) and after (09:19) the outage of the Krško NPP unit and the 400 kV node Tumbri are also shown in Figures 1 and 2.

Demand in the Croatian power system immediately before the disturbance was 1860 MW and was covered by production from domestic sources of 1478 MW and from import of 382 MW (including 50% of power from Krško NPP or 257 MW). Roughly two thirds of the import balanced the southern part of HR system and one third was used to balance the wider Zagreb area. The notified transit of active power through HR system for BiH system was 160 MW and the undeclared transit for an unknown user was 280 MW. Due to an especially long dry period most of production within the HR system originated from thermal power plants located in the wider Zagreb area (about 620 MW) and from thermal power plants in the western part of HR system (TPP Rijeka and TPP Plomin 1 and 2 whose total dispatched power was about 600 MW). These sources were connected to the 110 kV and 220 kV levels of the transmission network not affected by the disturbance which proved to be of decisive importance for maintaining the overall stability of the Croatian system in this particular case..

## 3. CHRONOLOGY OF EVENTS

The situation before the disturbance in all power systems considered was normal. The disturbance began by the outage of the NPP Krško unit (09:15:10.008) during a routine testing, whose production at the time was 514 MW. Loss of this production caused power flow to increase on the 400 kV line Hévíz – Tumbri after which circuit breaker failure protection (CBF protection) was quickly activated in the 400 kV bay Hévíz in Tumbri substation (at 09:15:10.374). This protection switched off the circuit breaker in the 400 kV bay Tumbri in Hévíz substation, all 400 kV lines connected to the Tumbri node and all three 400/110 kV transformers through which the local power system of Zagreb and its surroundings is supplied from the 400 kV network. Based on the checking done at operator level, it was concluded that the circuit breaker in the bay Hévíz in Tumbri substation was o.k. and at 09:30 a switching on was attempted of all 400 kV circuit breakers in Tumbri substation with the circuit breaker in the 400 kV bay Hévíz being the last to be switched on. However, when it was switched on (09:35:12.613) CBF protection was activated again (09:35:36.679) and all elements connected to the 400 kV node Tumbri were switched off. It was concluded that the circuit breaker in the 400 kV bay Hévíz needed detailed examination and that it should not be switched on until further notice. In the next attempt, the 400 kV node Tumbri was successfully reconnected without the 400 kV line Tumbri (HR) – Hévíz (H). The system operator compensated for the loss of production (NPP Krško) in the Croatian power system by dispatching hydro generating units in the southern part of the system (Senj, Orlovac and Zakučac hydro power plants).

A specialist checking of the circuit breaker and relay protection (Figures 3 and 4) in the bay Hévíz of Tumbri substation (from 09:40 to 11:15) determined that the circuit breaker was in the proper working order and that the cause of the fault was the welded contact of the auxiliary relay in the line protection REL 531 which starts CBF protection (Figure 4). The contacts of that relay in the line protection REL 531 are not overseen by the watchdog function. The technical defect was removed by switching off in REL 531 the START-signal for CBF protection and at the same time the current threshold in CBF protection (Figure 4) was retuned from 1300 A to 1800 A. After that, at 11:21 the 400 kV line Tumbri – Hévíz was also switched on. It remained to be determined at a later point why the “welding” had occurred of the auxiliary relay in REL 531.

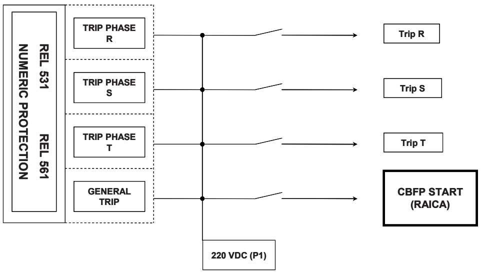



**Figure 3** Binary output configuration of numeric line protection tripping circuits

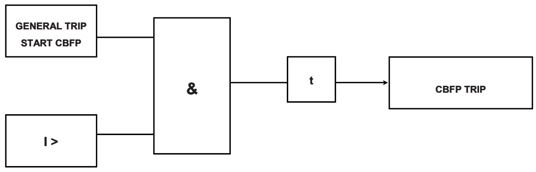



**Figure 4** Block diagram of CBF protection

The redistribution of power flows in the central part of the UCTE system (Hungary, Austria, Czech Republic,…) caused by the outage of NPP Krško and of the 400 kV node Tumbri especially in Austria’s transmission network caused overloading of the 220 kV lines and consequent activation of the system protection ( “Sollbruchstelle”) which at 09:19:14 switched off the 400 and 220 kV connections toward the Czech Republic (Dürnrohr – Slavetice and Bisamberg – Sokolnice). There ensued a dangerous loading of the lines between Austria and Hungary and dropping of voltage in the Austrian system (e.g. to the level of 91% in the node Obersielach 380). At the same time voltage in the Slovenian system fell considerably. For instance, in the 400 kV node Krško, the voltage dropped below 360 kV. The situation in the Slovenian and Austrian power systems was normalized by dispatching reserves and increasing production of reactive power in generating units.

## 4. SYSTEM DYNAMICS RECORDING IN THE POWER SYSTEM OF CROATIA

During the disturbance described above, active power flows on the lines between Croatia and Slovenia and Hungary (Figure 5) and system frequency (Figure 6) were recorded in the Croatian power system. Figure 4 shows that the outage of a Krško generating unit caused frequency to fall by about 27 mHz. This frequency drop is relatively well correlated with the production loss of 514 MW and the regulation constant of the UCTE system of about 20000 MW/Hz.

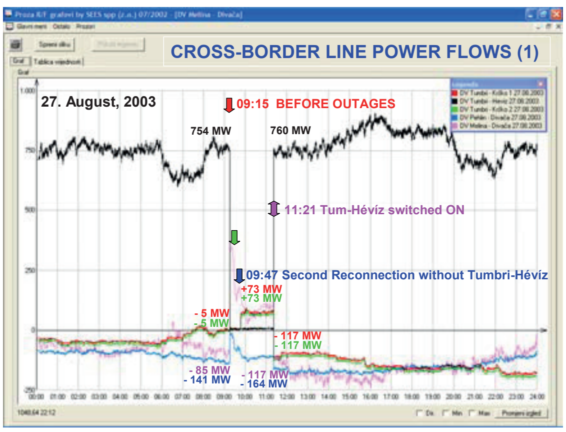



**Figure 5** Active power flows on lines between HR, SLO and H

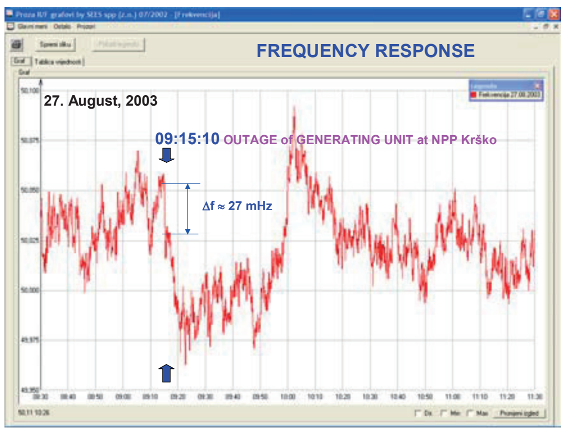



**Figure 6** System frequency chart

## 5. SIMULATION ANALYSIS

A simulation analysis on the dynamic system model has been carried out for the case of the actual sequence of events (outage of a Krško unit and consequent outage of the 400 kV node Tumbri) and for a hypothetical case consisting only of outage of the Krško unit. The objective of the simulation analysis was to preliminarily investigate:

- power flows dynamics on the characteristic lines in the Croatian power system for assessment of congestion risk, and the current dynamics on the 400 kV line Tumbri – Hévíz for analysis of CBF protection action,
- dynamics of the Croatian power system and to assess the security of the Croatian system primarily using the criterion of voltage stability and the criterion of angle stability because at that time Croatian and BiH systems were on the perimeter of the UCTE system with a characteristic mode of inter-area oscillations (with period 1.2 to 1.4 s) of a group of hydro generating units in the southern parts of the Croatian and BiH systems,
- voltage dynamics in the Slovenian system and an assessment of the trend of voltage profiles in the first 15 seconds because this system experienced a considerable loss of production in the immediate proximity of the border with the Croatian system.

The investigations were carried out using an appropriate software package for the calculation of stability on a multimachine dynamic model which comprises the power systems of Croatia and BiH (detailed model at 400, 220 and 110 kV levels), Slovenia,, Austria, Hungary, northern Italy, Slovakia and the Czech Republic (400 and 220 kV) and dynamic equivalents of the remaining part of the UCTE system.

The configuration and steady state of the system were so set as to match as much as possible the situation immediately before the event (27 August 2003 at 09:15). Power system dynamics during first 15 seconds was simulated.

Considering dynamics of active power flow (Fig. 7) and current (Fig. 8) on the 400 kV line Tumbri – Hévíz, voltage dynamics of the 400 kV node Tumbri (Figure 11), time needed for current on the line Tumbri – Hévíz to reach the overcurrent threshold of CBF protection (1300 A) following the outage of a NPP Krško unit, and considering response time and delay of CBF protection operation and circuit breaker closing time, it is estimated that active power on the 400 kV line Tumbri – Hévíz at the moment of its switching off was about 900 MW. This is almost 20% higher than the power flow read from the recorded trend curve shown in Figure 5. The results of the simulation show us that the power of the disturbance was considerably greater than the one that could be read from available records. WAMS system would certainly allow a much better insight into the system in this particular and any similar situation.

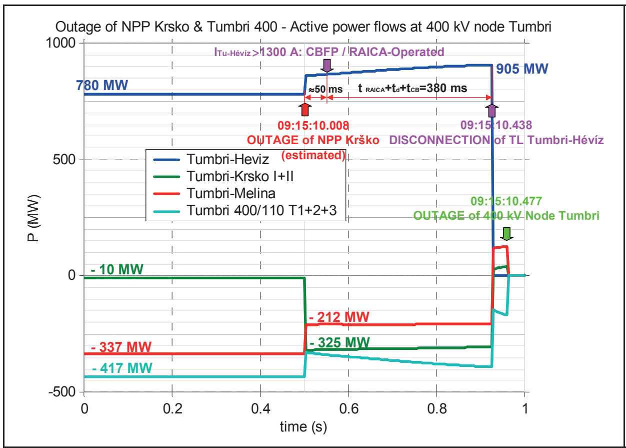



**Figure 7** Active power flow on lines connected to 400 kV node Tumbri (outage of NPP Krško and 400 kV node Tumbri)

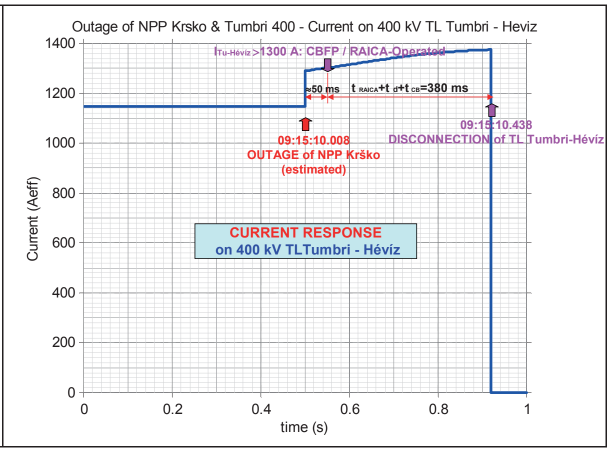



**Figure 8** Current on 400 kV line Tumbri (HR) – Hévíz (H) - (outage of NPP Krško and 400 kV node Tumbri)

The simulation analysis of power flow dynamics for both the actual event (outage of a NPP Krško unit and the 400 kV node Tumbri) as illustrated in Figure 9 and for a hypothetical event (outage of a NPP Krško unit only) as illustrated in Figure 10 shows that the security of the Croatian power system was not jeopardized during the event, neither by congestion/overloading of system elements nor by dangerous lowering of voltages. The results of the simulation analysis of voltage stability are illustrated in Figure 11 for the actual event of outage of the NPP Krško unit and the 400 kV node Tumbri and in Figure 12 for the hypothetical event (outage of the NPP Krško only).

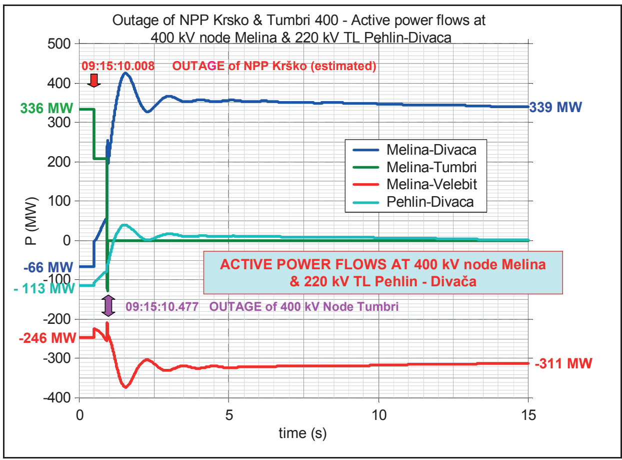



Figure 9 Active power on characteristic lines (outage of NPP Krško and 400 kV node Tumbri)

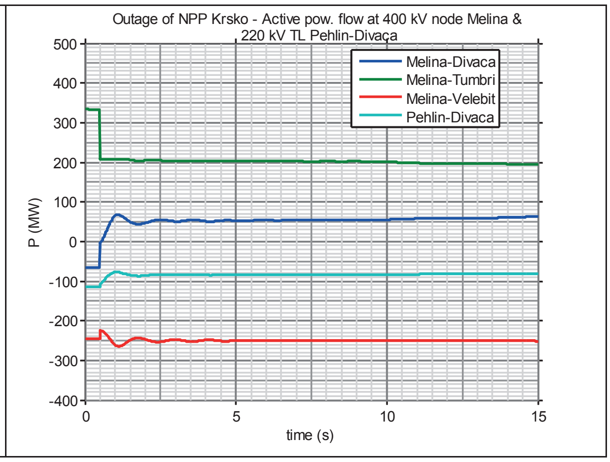



Figure 10 Active power on characteristic lines (outage of NPP Krško only)

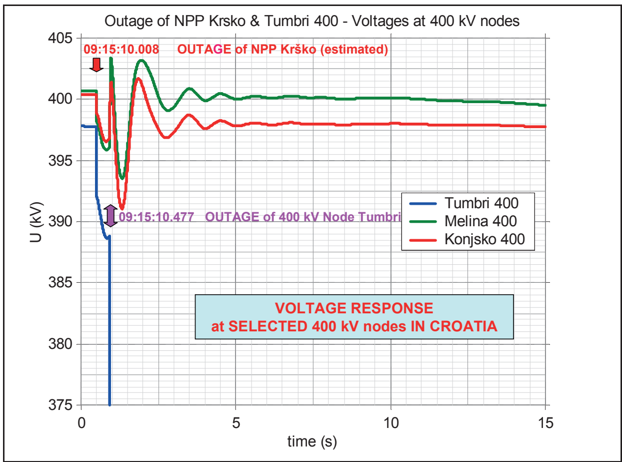



Figure 11 Characteristic bus voltages in HR system (outage of NPP Krško and 400 kV Tumbri)

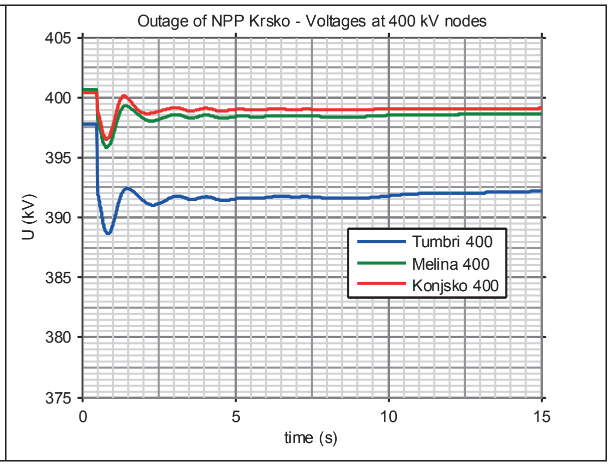
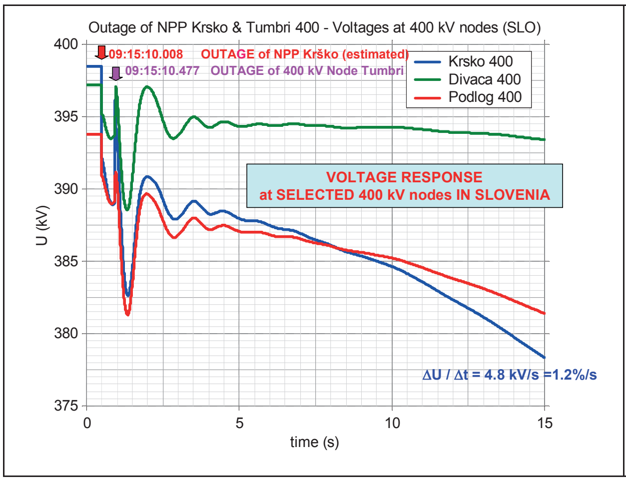



Figure 12 Characteristic busvoltages in HR system (outage of NPP Krško only)

Regarding the security of the Slovenian system using the criterion of voltage stability, the simulation analysis shows and confirms that for the case of the actual event (outage of a Krško unit and the 400 kV node Tumbri), the critical situation was in the vicinity of the Krško substation. Voltage conditions in the Slovenian system are illustrated by voltage dynamics at characteristic points of the Slovenian system shown in Figure 13 for the case of the actual event and for the case of the hypothetical event (outage of a Krško unit only) in Figure 14. The results of the investigation show that for the case of the actual event the Slovenian system in the vicinity of Krško substation was on the brink of voltage collapse. For example, the rate of voltage decrease in the 400 kV node Krško (Fig. 13) at the end of the simulation period was 4.8 kV/s or 1.2%/s. In the case of outage of a Krško unit only, the simulation analysis shows (Fig. 14) that the voltage stability of the Slovenian system would not be jeopardized. It would be interesting to carry out a simulation analysis aimed at assessing the justifiability of activation of the system protection in the Austrian system in this particular case (outage of a Krško unit and the 400 kV node Tumbri).



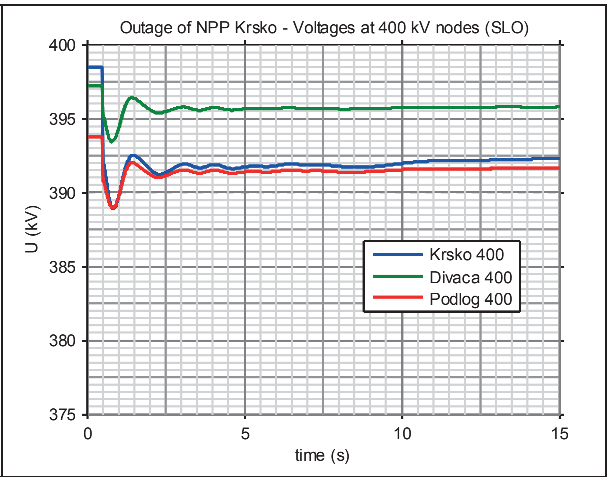



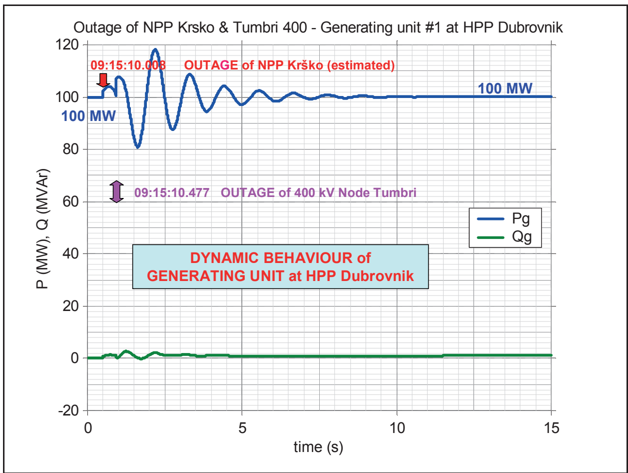

**Figure 13** Voltage at characteristic nodes of Slovenian system (outage of NPP Krško and 400 kV node Tumbri)

**Figure 14** Voltage at characteristic nodes of Slovenian system (outage of NPP Krško only)

It is characteristic of the Croatian and BiH systems that their hydro units in the southern parts of the system form a coherent group with the mode of inter-area electro-mechanical oscillations whose period varies between 1.2 s and 1.4 s depending on dispatching of these units. This oscillation mode and its characteristics were used to assess system security using the criteria of small signal angle stability. For this purpose the dynamics of system frequency was analyzed at characteristic system points as well as dynamics of power of generating units.

A generating unit of the Dubrovnik hydro power located at system perimeter has been chosen for illustration (Figure 1). The dynamics of active and reactive power of this unit for the case of the actual event (outage of NPP Krško and the 400 kV node Tumbri) is given in Figure 15 and in Figure 16 for the hypothetical case (outage of NPP Krško only). Roughly, based on the dynamics of active power of the unit, for both cases the oscillation frequency of this inter-area mode was 0.89 Hz, oscillations were well damped ($\zeta_1$=0.117 in the actual event, $\zeta_2$=0.095 in the hypothetical case) while the maximum elongation of the generator active power was 38 MWpp for the actual event as opposed to 16 MWpp in the hypothetical case.

In conclusion, the security of the Croatian system using the criterion of angle stability was not jeopardized during the actual event.



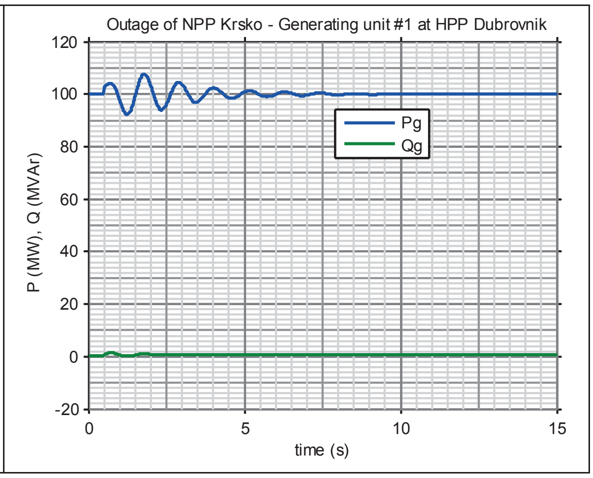




**Figure 15** Dynamic behavior of a generating unit of HPP Dubrovnik (outage of NPP Krško and 400 kV node Tumbri)

**Figure 16** Dynamic behavior of a generating unit of HPP Dubrovnik (outage of NPP Krško only)

## 8. CONCLUSION

The outage of a generating unit of NPP Krško (SLO) and outage of the 400 kV node Tumbri (HR) was a major disturbance which jeopardized in particular the Austrian and Slovenian systems. The outage of the 400 kV node Tumbri was due to the failure of an auxiliary relay in the line protection of the 400 kV line Tumbri – Hévíz which is not supervised by the watchdog function.

Overloads and consequent tripping of lines led to the weakening of connections within the UCTE system and/or to diminished operational security of all the systems affected.

The security of the Austrian system was jeopardized judging by the line overloads and voltage stability criterion.

The Slovenian system security was jeopardized judging by the voltage stability criterion. Area in the vicinity of the Krško nuclear power plant was on the brink of voltage collapse.

The security of the Croatian system was maintained across all the criteria considered: voltage stability, angle stability and the line congestion / overloads. During the disturbance, the operational security of the Croatian system was diminished due to unavailability in the transmission network.

The simulation analysis has provided a more precise insight into power system dynamics during the first 15 seconds of the disturbance. The results of the simulation for the hypothetical case of outage of NPP Krško show that it would be a local disturbance for the UCTE system. Use of WAMS would greatly enhance observability of power system dynamics.

It would be interesting to carry out a simulation to investigate the justifiability of activation of system protection in the Austrian system in this particular event.

Also, based on the experiences with this event a question arises of how to make a timely determination of hidden faults of relay protection and whether regular testing procedures should be amended accordingly.

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