# LARGE DISTURBANCE IN CROATIAN POWER SYSTEM RESULTING IN TRANSIENT INSTABILITY AND OUTAGES OF THREE MAJOR THERMAL UNITS

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## 1. INTRODUCTION

Large disturbances in power systems are usually triggered by some initial fault and then spread over the system due to combined effect of many reasons such as malfunctioning or improper operation of equipment, human faults, lack of appropriate information, etc. It is duty of power system analysts to identify, based on disturbance analysis results, such weaknesses in power system operation and to suggest measures to be taken.

Quality of the disturbance evaluation largely depends on quality of available records of the event. Traditionally, the main sources of information were sequence-of-events records from data loggers installed at various plants in the system, complemented with information collected from operating personnel and records from chart recorders. Nowadays there is another valuable source: digital fault recorders, i.e. devices designed to automatically record various waveforms (usually instantaneous values of voltages and currents) and binary signals from the plant where they are installed. Due to advance of numerical technology fault recorders are now widely used and have become a standard feature of modern numerical protection equipment. Recorded signals are easily transferred to standard computers for further analysis.

However, it must be kept in mind that these devices are primarily intended for recording of locally measured quantities, during several seconds or less, and not for the system-wide monitoring. Also, they are not necessarily time-synchronised and coordinated so that great care should be exercised if they are used in reconstructing sequence-of-events. Having said that, it must be stressed that fault recorders generally are great aid and have brought a new quality to evaluation of disturbances.

Further step in this direction is introducing system-wide integrated and coordinated monitoring and protections schemes.

Simulation analysis can be of great help in understanding development of disturbance under examination. Sequence of events could be much easier reconstruced if the system behaviour before and during the disturbance could be reproduced by means of a simulation model, capable of representing at least most important aspects of the event. Good dynamic simulation models are prerequisite for succesful simulation analysis. Matching simulation results against recordings from the real system is practically the best way to validate the models. Very often it appears that some additional fine tuning of models is necessary. In any case model limitations should be carefully considered in judging the credibility of simulation results.

This paper deals with the large disturbance in Croatian power system that occured on 20th September 2002 at 00:19:02. The disturbance was triggered by a three-phase short circuit on a 220 kV transmission line and resulted in transient instability and tripping of three large thermal units in the region of Istria and Northern Adriatic. The process of disturbance evaluation and analysis is outlined, indicating difficulties encountered and possible improvements, and the simulation model is described. Simulation results are compared with records from the real system, showing how information from fault recorders enhanced our understanding of phenomena involved. In conclusion, some possible improvements and actions to be taken in order to reduce the probability of such events are discussed.

## 2. DEVELOPMENT OF DISTURBANCE

As already mentioned, the disturbance started on September, 20th 2002 at 00:19:02. According to the snapshot obtained from the DAM (Dispatcher Network Analysis System) at the National Dispatching Centre in Zagreb, the steady state of Croatian power system at 00:17:28, i.e. immediately before the disturbance, was as shown in Fig. 1. Croatian power system is operating as a part of UCTE interconnection.

Three thermal units were in operation in the Istria and Northern Adriatic area of Croatian power system: TPP Rijeka (with 202 MW or 63% of the unit's rated active power), TPP Plomin 1 (with 108 MW or 90% of its rated MW) and TPP Plomin 2 (with 195 MW or 94% of the unit's rated active power). Total production of those three units was 505 MW or 53% of total generation in Croatian system.

Connection of the three above mentioned thermal units to the power system is shown in Fig. 2.

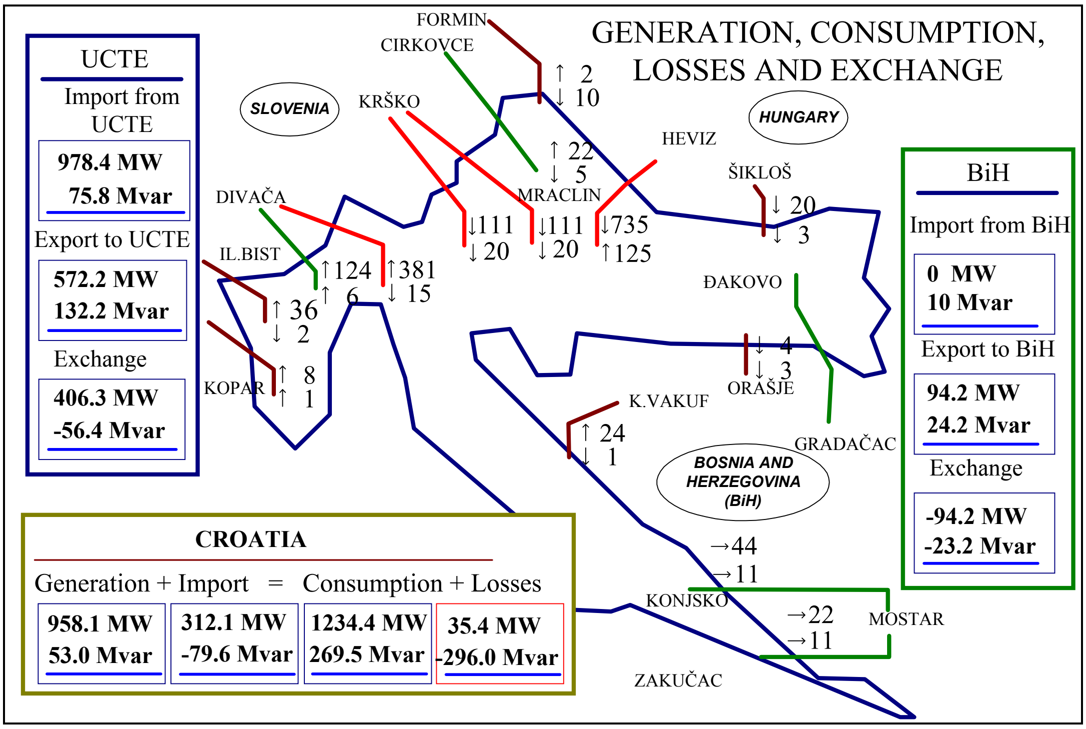

**Figure 1** Totals and tie-line power flows of Croatian power system on 20th September 2002 at 00:17:28, i.e. immediately before the disturbance

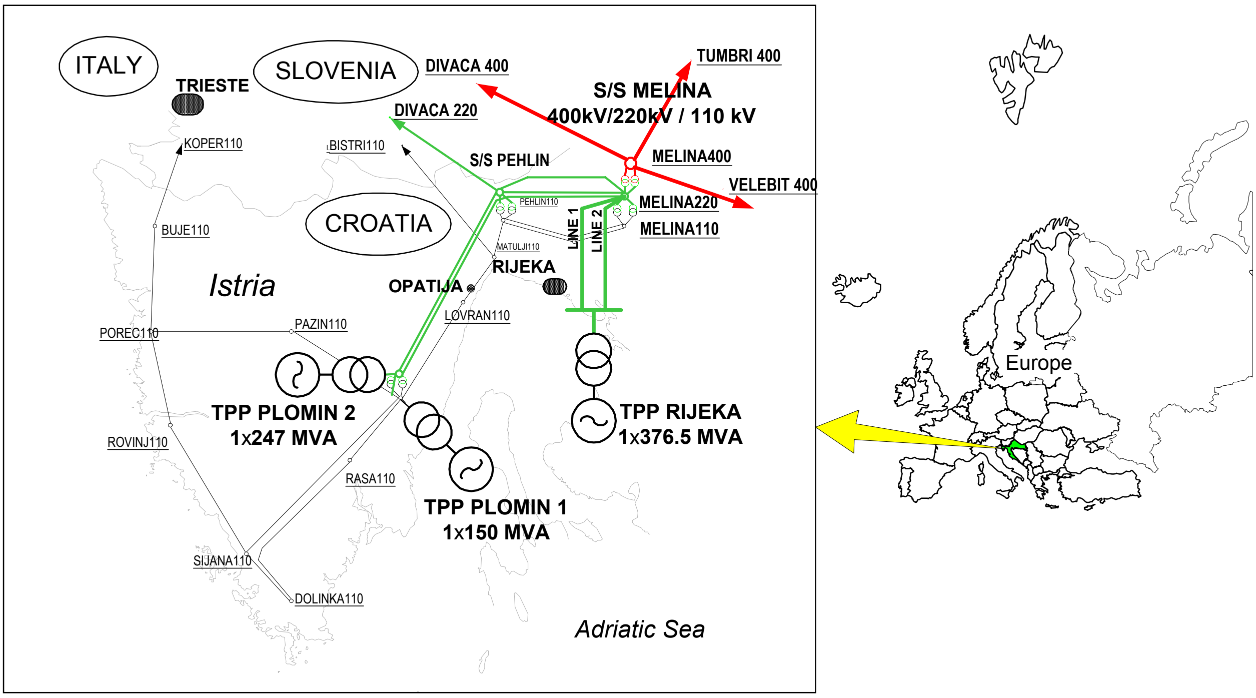

**Figure 2** Connection of three thermal units in the Istria and Norhern Adriatic to the power system

During the night of 20th September there was a heavy thunderstorm that caused many transient faults on transmission lines in this area and consequently many repeated operations of distant protections followed by single-phase automatic reclosures. Protection operations due to single line-to-ground were registered also in each of three phases at transmission lines TPP Rijeka – S/S Melina 1 and 2 (see Fig.2). At one moment, due to some unknown reason, the 220 kV line TPP Rijeka – S/S Melina 2 was suddenly disconnected at the S/S Melina end and the line remained energized from TPP Rijeka. In such conditions, and with insulation strength of the air already reduced because of previous ionisation, a three-phase short circuit occured on the line, most probably caused by yet another stroke of lightning. It should be noticed that the three-phase fault developed exceptionally quickly as can be seen from the instantaneous values of currents and voltages recorded by REL 521 numerical line protection relay at TPP Rijeka (see fig A-2 in Appendix). Total fault impedance seen from the busbars at TPP Rijeka was approximately 2.5 Ohms. The very short transmission line TPP Rijeka – Melina 2 (6 km) was protected on both ends by solid-state distance protection relays (type RAZOA – ASEA) with usual settings of 90% of the line length (1.705 Ohm) in the first zone. Since the total fault impedance was greater than its first-zone setting the relay could not have operated in the first zone. Also there was no communication signal sent because the relay at the opposite end could not detect the fault since the respective circuit breaker was open and echo logic is not supported by this type of relay. The fault was therefore cleared by the operation of distance protection in the second zone with time delay of 500 ms so that the total duration of the fault amounted to 640 ms. That was very severe disturbance for the system and especially for nearby generators. All three thermal units in this area had lost transient stability and went into out-of-step operation (as detected by means of simulation). The unit at TPP Plomin 1 was tripped first (at 1.469 seconds after inception of the fault) but it could not have been determined which one of its protections actually caused tripping. Soon after that (at 1.661 seconds after the occurrence of the fault) the unit at TPP Rijeka was disconnected by its loss-of-excitation protection. Surprisingly, no electrical protections of the TPP Plomin 2 generator operated and the unit remained connected and running in out-of-step condition until it was tripped (at 9.232 seconds after the inception of the fault) by the protection against low cooling oil pressure of the coal mill reductor (as a consequence of lowered voltage at the unit auxiliaries busbars during the disturbance).

Due to the fact that the Croatian system was in parallel operation with the UCTE interconnection and well connected to it, the system was able to achieve a new stable steady state in spite of sudden loss of the three large units with total production of 505 MW. Unbalance that occurred in the Croatian power system was at

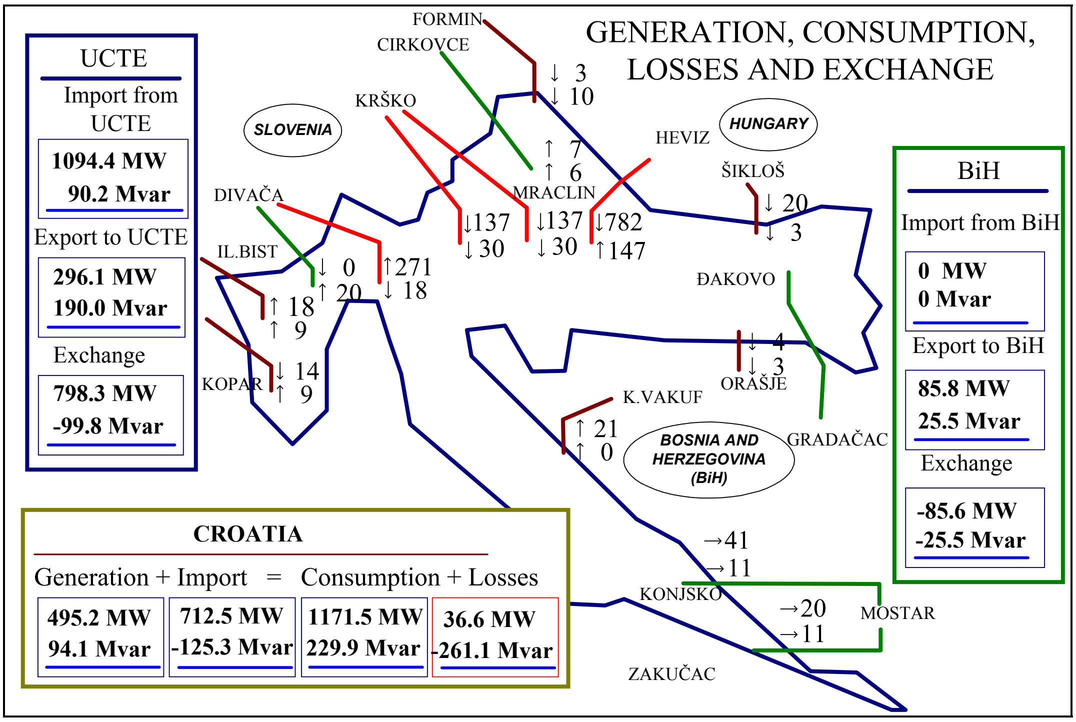

**Figure 3** Totals and tie-line power flows of Croatian power system after loss of three thermal units with total generation of 505 MW (on 20th September 2002 at 00:30:05)

first moment covered mainly by drawing the primary regulation reserve from UCTE. During next couple of minutes several hydro units in the southern part of the system were started which helped to restore the balance of Croatian system.

Totals and tie-line interchanges of the Croatian system at the steady state immediately following the tripping of the generating units at TPP Rijeka, TPP Plomin 1 and TPP Plomin 2 are shown in fig 3 (system snapshot was taken by DAM on 20th September at 00:30:05). At that moment the Croatian system was still being importing approximately 400 MW of unscheduled (emergency) power from the UCTE.

## 3. ANALYSIS OF DATA RECORDS

The following sources of information were used as a basis for evaluation of disturbances:

- system configuration and steady state snapshots taken by DAM at the National Dispatching Centre in Zagreb
- sequence-of-events lists from TPP Rijeka, TPP Plomin 1, TPP Plomin 2 and the area control centre Pehlin
- instantaneous values of currents and voltages recorded by the following numerical line protections:
  - REL 521 at TPP Rijeka, 220 kV line TPP Rijeka – Melina 1 (recording only)
  - REL 521 at TPP Rijeka, 220 kV line TPP Rijeka – Melina 2 (recording only)
  - REL 531 at TPP Plomin, 220 kV line TPP Plomin – Melina (recording and protection)
  - REL 531 at TPP Plomin, 220 kV line TPP Plomin – Pehlin (recording and protection)
- report on the disturbance, prepared by Relay Protection Department, Transmission Area Opatija,
- distance protection test sheets from Relay Protection Department, Transmission Area Opatija,
- report on the disturbance from TPP Rijeka
- relay protection test sheets from TPP Rijeka
- report on the disturbance, prepared by TPP Plomin 1 and TPP Plomin 2 staff
- relay protection test sheets from TPP Plomin 1 and TPP Plomin 2
- information collected from operating personnel

The sources were compared and analysed in order to:

1. establish the physical background and reconstruct the development of the entire disturbance
2. identify the initial fault
3. determine the nature and estimate severity of the disturbance
4. determine what aspects of power system security were endangered / lost
5. review the electrical protection performance
6. review the behaviour of generating units and their associated control and protection systems

Unfortunately, the sequence-of-events record from S/S Melina, the one that would be of great importance for the analysis, was not available because of failure of the data logger installed at that substation. At the start of the analysis it was even not evident that the line TPP Rijeka – S/S Melina 2 had been open at the side of S/S Melina just prior the three-phase fault.

In the course of analysis it became clear that the further analysis would rely heavily on information extracted from instantaneous values of currents and voltages recorded by numerical line protections. Those records are shown in the Appendix (fig. A-1, A-2, A-3 and A-4) of this paper. However, use of the records for the purpose of analysis was not quite straightforward as will be shown in the further discussion.

Fault disturbance facilities of line protections are designed for recording of power frequency transients and not for power swings and similar slower phenomena. The whole time span of the disturbance which in this case lasted for nearly 10 seconds (i.e. till tripping of the last generator) was not recorded by relays as contiguous waveforms. It was necessary to „patch“ the records in order to reconstruct the entire period of observation. This was not easy because the relays were not synchronised with a common time base. First the proper time relationship between consecutive records ("segments“) had to be established for data recorded by each individual relay. When this was done for all relays, the completed ("reconstructed") records from different relays could be time-aligned. The just described reconstruction process is illustrated by waveforms recorded by relays in the 220 kV lines TPP Plomin – S/S Pehlin (two segments, see App. fig. A-3) and TPP Plomin – S/S Melina (three segments, see App. fig. A-4).

Once the records were reconstructed and synchronised the characteristic events such as occurrence of the fault, clearing the fault and tripping of the generating units could be marked on the time axis. Close inspection of current and voltage waveforms recorded by the relay in the 220 kV line TPP Rijeka – S/S Melina 2 shows that the three-phase short circuit on that line occurred practically instantaneously in all three phases (see App. Fig. A-2). Recorded waveforms clearly show the dynamics of currents and voltages during fault while their envelopes in the post-fault period reflect the power swings in the system caused by pole slips of the generators during their out-of-step operation.

In conclusion, in spite of the aforementioned difficulties the recordings made by numerical line protections were of greatest importance not only for evaluation of current-voltage relationships during the fault but also for the analysis of subsequent power system dynamics.

## 4. SIMULATION ANALYSIS

The best way to confirm strong indications that the observed dynamic behaviour of the system was actually caused by out-of-step operation of large machines was to simulate the disturbance scenario using a suitable dynamic model and then to compare the obtained simulation results with recorded quantities from the real system.

Simulation analysis was performed using a standard non-linear multimachine dynamic model for stability analysis. The model comprises a detailed model of power systems of Croatia and Bosnia and Herzegovina at 400, 220 and 110 kV levels, models of power systems of Slovenia, Hungary, Austria, northern Italy at 400 and 220 kV levels and an equivalent representation of the UCTE / CENTREL interconnection also at 400 and 220 kV levels. Synchronous machines are generally modelled at subtransient level with excitation control systems and turbine governors (except large equivalents in the UCTE / CENTREL part of the model). The simulation package used for the analysis did not allow representation of protective relaying. Switching actions caused by protection operation were modelled as forced switchings in the simulation scenario, at exact times of real events taken from the synchronised sequence-of-event lists.

Initial steady state was first adjusted so as to approximately match the pre-fault conditions retrieved from the DAM system at the National Control Centre in Zagreb (output of the state estimator was used for that purpose). Three-phase fault at the open end of the 220 kV line TPP Rijeka – S/S Melina 2 was simulated. Fault impedance was determined as the difference between the total impedance seen during fault by the numerical line protection in the line bay "Melina 2" at TPP Rijeka, and the known line impedance.

Some minor corrections of the model needed to be done after trial simulation runs. After that a rather good accordance between simulation results and available recordings from the system has been achieved. This comparison helped to finally conclude that the three thermal units had lost synchronism.

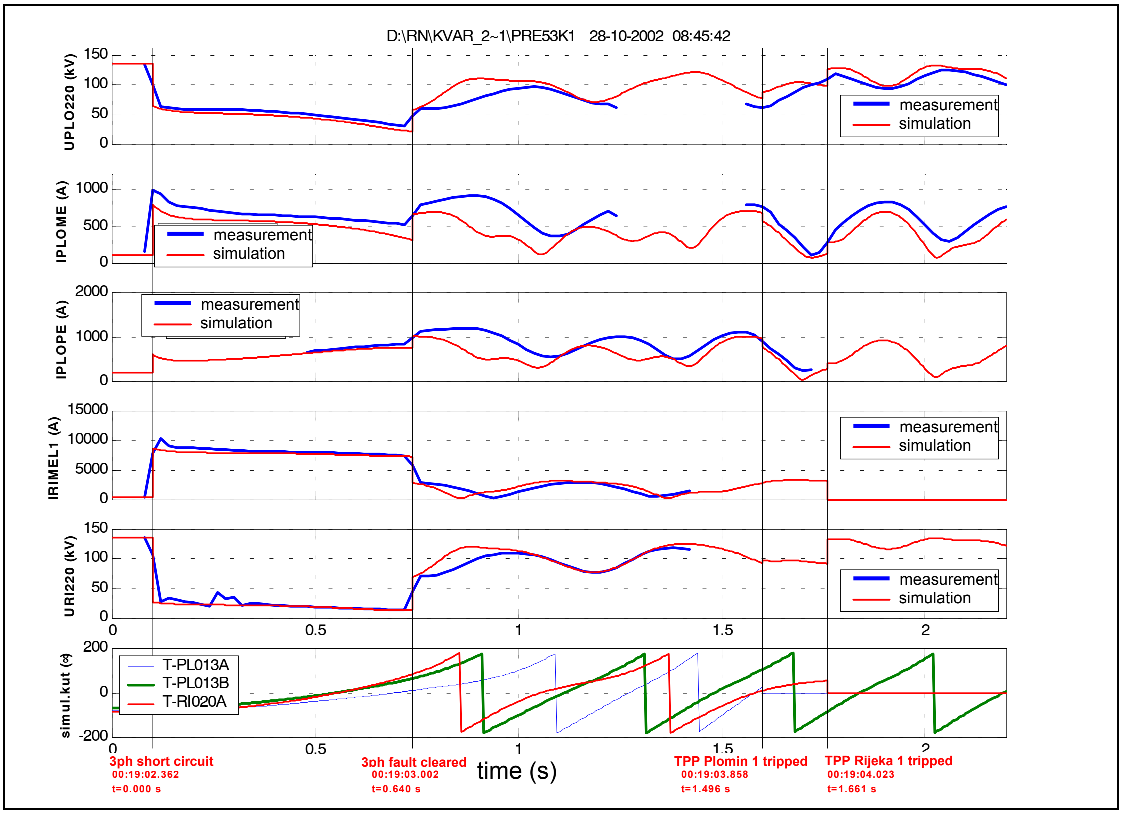

**Figure 4** Comparison of simulated and recorded characteristic quantities during disturbance of 20th September 2002, with rotor angle dynamics from the simulation (T-PL013A=TPP Plomin 1; T-PL013B=TPP Plomin 2; T-RI020A=TPP Rijeka)

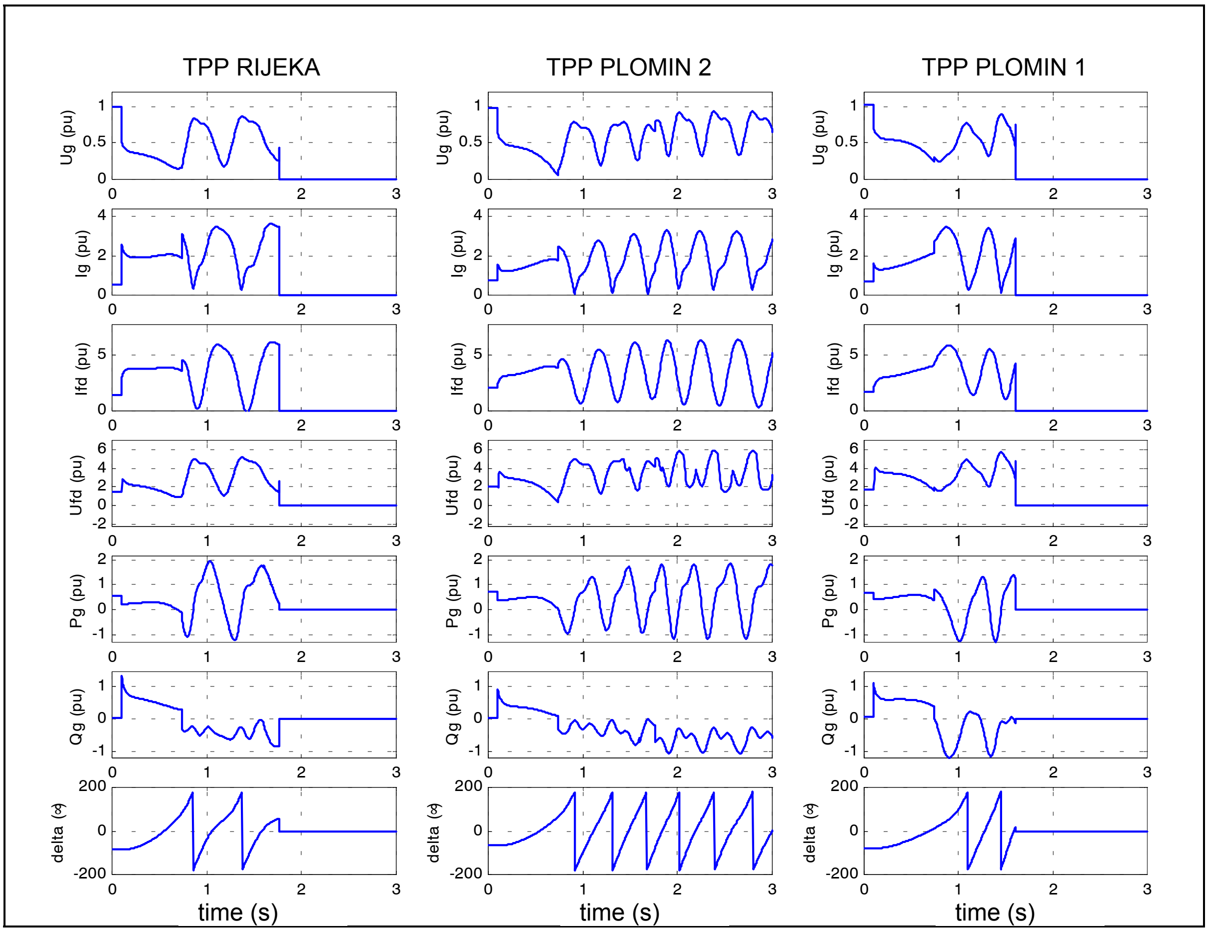

**Figure 5** Variables of generating units at TPP Rijeka, TPP Plomin 1 and TPP Plomin 2 during the disturbance disturbance of 20th September 2002 (simulation results)

A comparison of simulation results with measurements (RMS values) is shown in Fig. 4. (shown quantities are designated as follows: UPLO220 – 220 kV voltage at TPP Plomin; IPLOME – current in the 220 kV line TPP Plomin – S/S Melina; IPLOPE – current in the 220 kV line TPP Plomin – S/S Pehlin; IRIMEL1 – current in the 220 kV line TPP Rijeka – S/S Melina 1; URI220 – 220 kV voltage at TPP Rijeka). Since the match between simulation and measurements was pretty good it allowed us to use simulation model results to estimate response of other quantities that had not been recorded, such as rotor angle of the generatos (Fig. 4 at the bottom) or representative variables for all three generators shown in Fig. 4 (Ug – generator voltage; Pg – generator active power; Qg – generator reactive power; Ig – generator current; Ifd – field current; Ufd – field voltage, delta – rotor angle with respect to the synchronous reference axis). Rotor angles clearly shows that the units at TPP Rijeka, TPP Plomin 1 and TPP Plomin 2 lost transient stability. Phase voltages at the 220 kV buses Plomin and TPP Rijeka indicate that voltage stability was also endangered.

As can be seen in fig. 4 the units at TPP Rijeka and TPP Plomin 1 were disconnected after two pole slips while the TPP Plomin 2 unit remained in asynchronous operation for nearly 9 seconds (note that only first three seconds are shown in Fig. 5). Operation of loss-of-excitation protection RAGPC (ASEA) at TPP Rijeka was correct and in accordance with its settings. The unit at TPP Rijeka is not equipped with a separate out-of-step protection but the loss-of-excitation protection is supposed to detect out-of-step conditions.

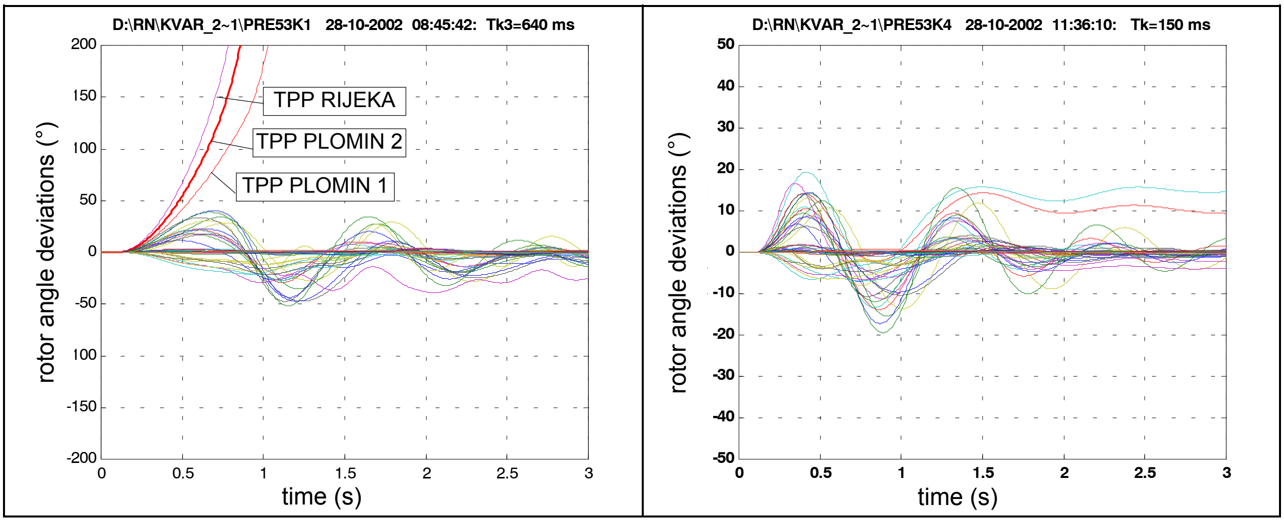

**Figure 6** Rotor angle deviations w.r.t. synchronous axis for the case of simulated real fault with duration of 640 ms (left), and for the same type of fault but with duration of 150 ms (right)

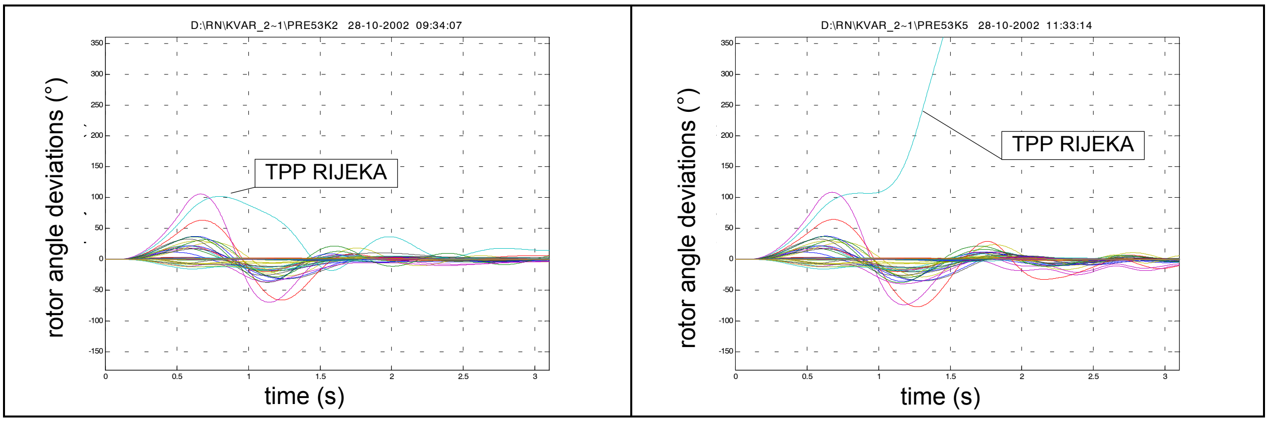

**Figure 7** Rotor angle deviations w.r.t. synchronous axis for critical clearing time of three-phase short circuit for the same initial steady state, type and location of fault as during disturbance of 20th September 2002

Once validated, the simulation model could be used for simulation of alternative scenarios. First of them to be simulated was the scenario with distance protection on the line TPP Rijeka – S/S Melina 2 operating in the first zone. Total fault duration in this case was set to 150 ms. In the sequel the critical clearing time was determined for the pre-fault configuration and steady state of Croatian system.

Rotor angle dynamics for all generators in the model is comparatively shown for the fault duration of 150 ms (fig. 6 on the right) and for the fault duration of 640 ms (fig. 6 on the left). As expected, transient stability would have been preserved had the distance protection operated in the first zone with assumed clearing time of 150 ms.

The next step was to determine the critical clearing time (CCT) for the case of three-phase fault and given initial power system conditions. Rotor angles dynamics for the critical clearing time (CCT) equal to 445 ms is shown in fig. 7 (left), while for the fault clearing time of 450 ms the unit at TPP Rijeka becomes unstable (fig. 7, right) and, by definition, transient stability of Croatian system is not preserved. It follows that for this specific case the second-zone time delay of the distance protection should have been reduced from 500 to 300 ms in order to avoid transient instability. But requirement for time coordination with circuit breaker failure protection (1st step: 150 ms; 2nd step: 300 ms) inhibits reducing second zone time delay of the distance protection to 300 ms. Other way to solve the problem is to protect these short transmission lines with line differential protection and this was chosen as final solution.

## 5. CONCLUSION

In the large disturbance described in this paper Croatian power system lost transient stability and was endangered from the voltage stability point of view.

After disconnection of generators that had lost stability the system fortunately attained a new stable state. This was possible mostly due to the fact that this area is well connected to the rest of Croatian power system and Croatian system itself was operating as a part of the large UCTE interconnection with which it was also well connected.

Although no loss of supply occurred it should be stressed again that this disturbance was very severe one for the system and extremely stressful to nearby generating units. The initial fault itself was practically ideal three-phase short circuit caused by atmospheric discharge. This case shows that even very unlikely faults may sometimes happen.

From the point of view of operational security of the system, the critical three-phase fault lasted much too long. Strictly speaking, the distance protection on the faulted line operated correctly but it is obviously inadequate for protection of such a short line. Reducing its second-zone time delay perhaps would have prevented loss of stability in this particular case but should not be done without careful assesment of potentially detrimental effects. Finally, it was recommended to install longitudinal differential protection in those two short lines. This was done within next few months and the differential protection is now installed and is in test operation mode.

This case has clearly shown that additional care should be put into protection coordination, particularly when lines connecting generating units to the system are concerned. Performance of the unit protection at TPP Plomin 2 was unsatisfactory from both unit's and system points of view and should be thoroughly revised, particularly regarding coordination with network protections. In addition, on basis of this disturbance analysis it was recommended that out-of-step protection and disturbance recorders should be installed at all three generating units (TPP Rijeka, TPP Plomin 1 and TPP Plomin 2).

Another conclusion is that high quality records of transients in the system are prerequisite for high quality of disturbance evaluation. Wider use of recording facilities in numerical protections is already an important step in that direction but the aim should be development of a coordinated and integrated system-wide monitoring scheme, based on dedicated disturbance recorders strategically placed at power plants and major substations. Security of supply and time synchronisation of existing data loggers and fault recorders are further issues to be addressed in the future.

Simulation models are powerful tools that could greatly enhance our understanding of complex system behaviour but they need to be premanently improved. Feedback from field measurements and recordings of system events should be more extensively used for validation and refinment of models.

## APPENDIX Current and voltage waveforms recorded by numerical line protections (instantaneous values, coordinated and time-aligned)

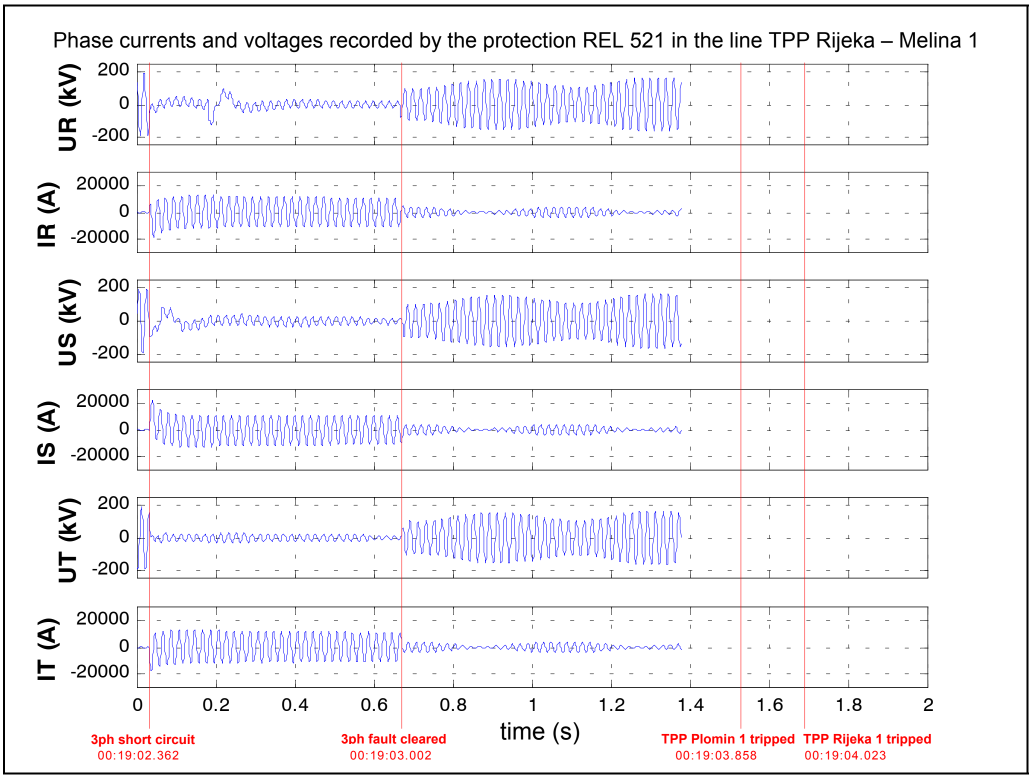

**Figure A-1** Current and voltage waveforms recorded by the line protection at 220 kV transmission line TPP Rijeka – S/S Melina 1 (at TPP Rijeka)

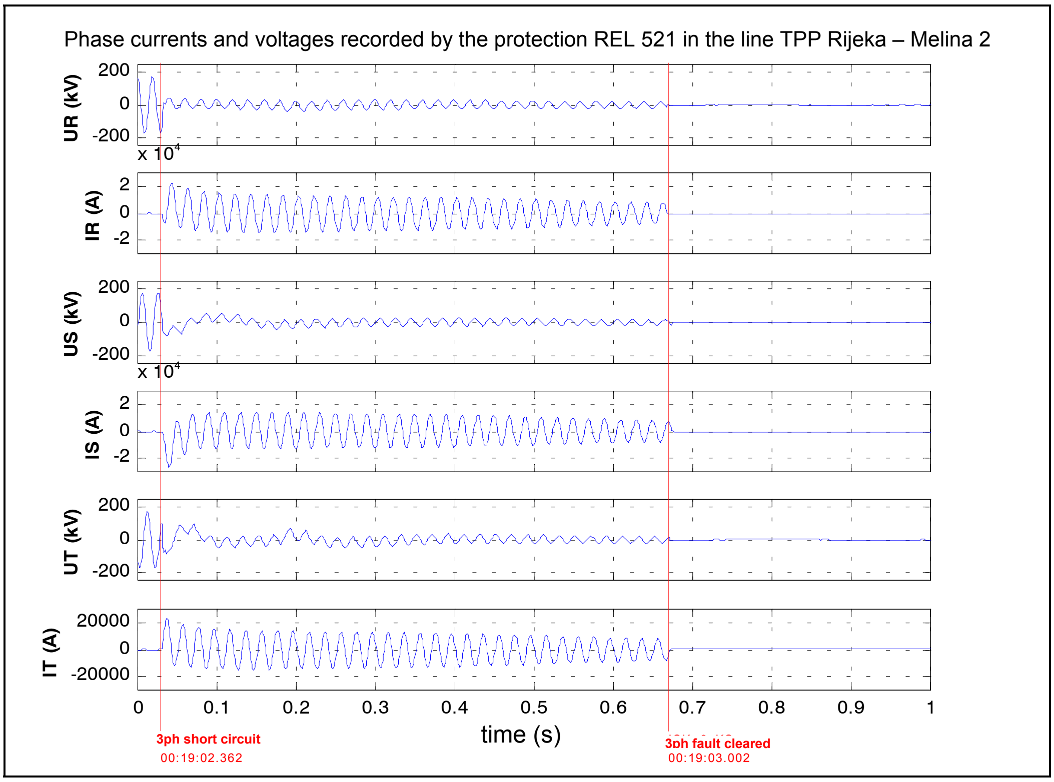

**Figure A-2** Current and voltage waveforms recorded by the line protection at 220 kV transmission line TPP Rijeka – S/S Melina 2 (at TPP Rijeka)

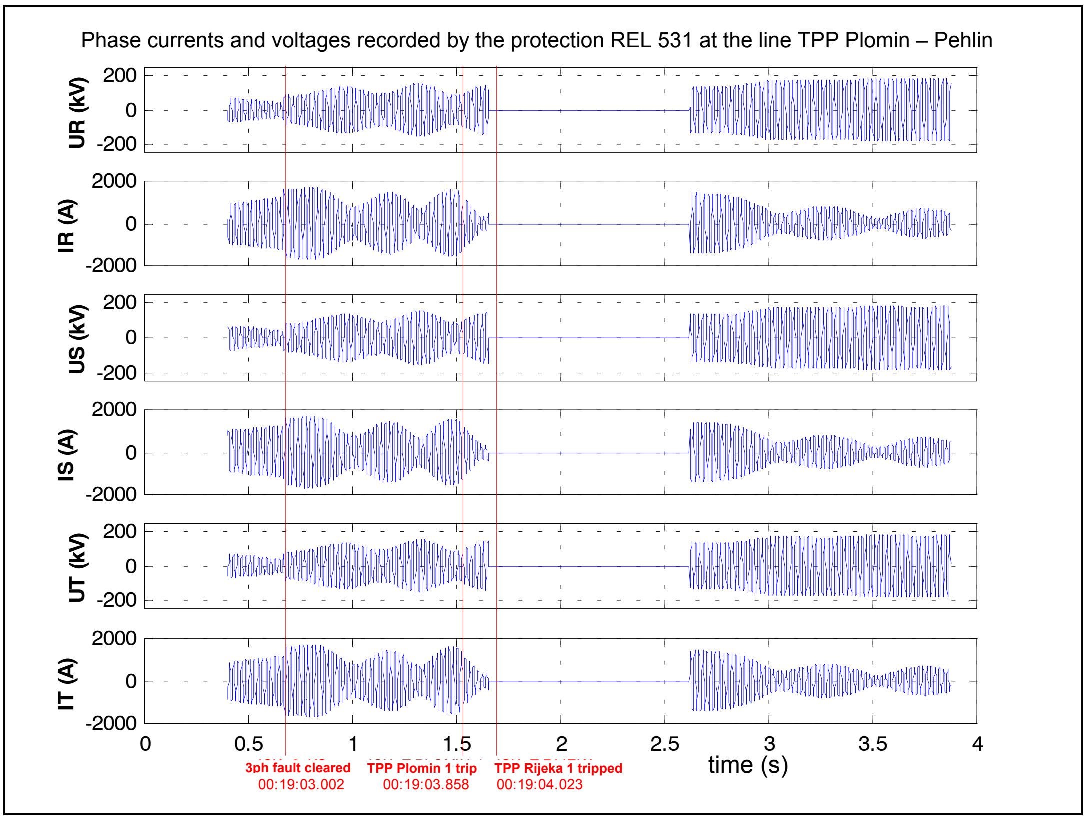

**Figure A-3** Current and voltage waveforms recorded by line protection at 220 kV transmission line TPP Plomin – S/S Pehlin (at TPP Plomin)

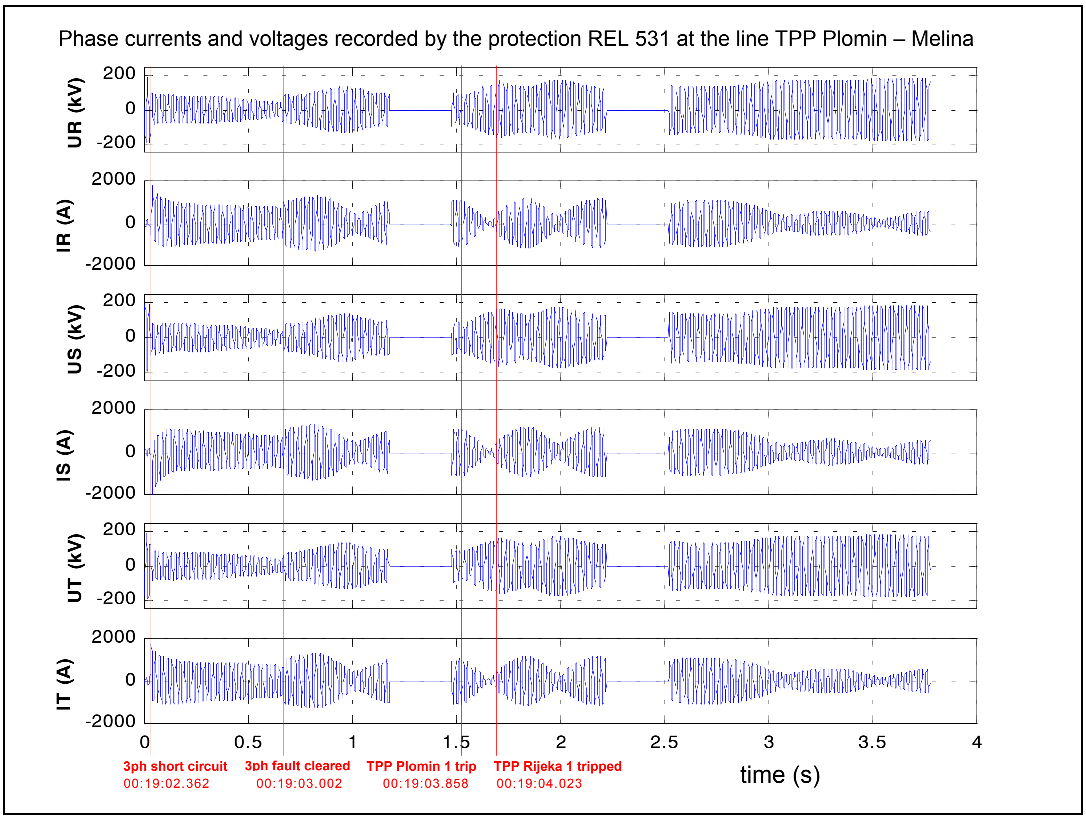

**Figure A-4** Current and voltage waveforms recorded by line protection at 220 kV transmission line TPP Plomin – S/S Melina (at TPP Plomin)