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POWER SYSTEM DYNAMICS DURING ISLANDING AND RECONNECTION OF POWER SYSTEM OF CROATIA AND BiH TO THE UCTE

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ABSTRACT
The paper deals with dynamic behaviour of Croatian power system during transients caused by switching off and on of the major tie lines between Croatian (HR) power system and UCTE, as well as during separation of power systems of HR and Bosnia and Herzegovina (BiH) from UCTE, their island operation and resynchronisation to the UCTE. These activities were part of the project of arranging phase sequence between HR and UCTE which was undertaken within scope of preparations for the reconnection of 1st and 2nd UCTE synchronous zones. Electromechanical transients of HR and BiH power systems are illustrated by measurement and simulation results. System dynamics during separation, islanding and resynchronisation of power systems of Croatia and BiH to the UCTE system was of special interest. In general, good agreement between measurement and simulation has been achieved but the simulation results are still rather conservative, indicating that the power system dynamic model need to be further improved. Organisation scheme of system-wide measuring and recording of representative quantities in the Croatian power system is also briefly outlined. It is shown that the Croatian and Slovenian power systems are crucial links in the transmission corridor from northeast to southwest part of UCTE.

KEY WORDS
power system dynamics, islanding, reconnection, electromechanical oscillations, measurement, simulation

1. Introduction

In course of preparation for the historical event of reconnection of the two UCTE synchronous zones that took place on 10th October 2004 there were many technical issues to be solved. Among other activities, Croatian electricity utility (HEP) was responsible for arranging the proper phase sequence alignment at the interface between Croatian power system and UCTE network. This technically and organizationally very challenging task required careful and comprehensive planning in order to minimize risks.

The interface between Croatian power system and UCTE includes tie lines between power systems of Croatia (HR) and Slovenia (SI) and Croatia and Hungary (HU) (see Fig. 1). Arranging phase sequence at that interface simply means interchanging positions of phase conductors (i.e. „transposing“, see Fig. 2) in each tie line at some convenient place.

In order to carry out the transposition of phase conductors, the tie lines (Fig.1) had to be disconnected one after another according to the predefined schedule. Disconnection of the last remaining tie line actually meant separation of the island comprising power systems of Croatia (HR) and Bosnia and Herzegovina (BiH) from UCTE. For security reasons it was necessary to keep duration of islanding as short as possible. On the other hand, at least one tie line with correctly arranged phase sequence must be available to make resynchronisation possible. For that purpose the transposition of phase conductors was done in advance in the three tie lines that had already been out of operation (400 kV line Tumbri – Krško 1 and 2 and 220 kV line Žerjavinec – Cirkovce, see Fig. 1) so that those three lines were ready for synchronisation prior to disconnection of other tie lines. According to the planned sequence of activities, the resynchronisation was to be done at S/S Tumbri by closing the circuit breaker at the 400 kV bay of the line Tumbri – Krško 1 under control of an appropriately tuned synchro-check relay. The other two lines (400 kV line Tumbri – Krško 2 and the 220 kV line Žerjavinec – Cirkovce) were to be switched on immediately after the successful resynchronisation.

Planning activities included determination of desired system conditions, defining of operational requirements and specification of all procedures. It was considered necessary to assess power system dynamic behaviour in the assumed scenario by means of dynamic simulation. Correctness of the synchro-check relay parameter settings could also be assessed in that way.

The unique opportunity to make recordings of system dynamics during such special and practically unrepeatable events was duly recognized. Such measurements not only deepen our knowledge and understanding of system dynamic properties but are of great value in validation of dynamic models and for various subsequent analyses.

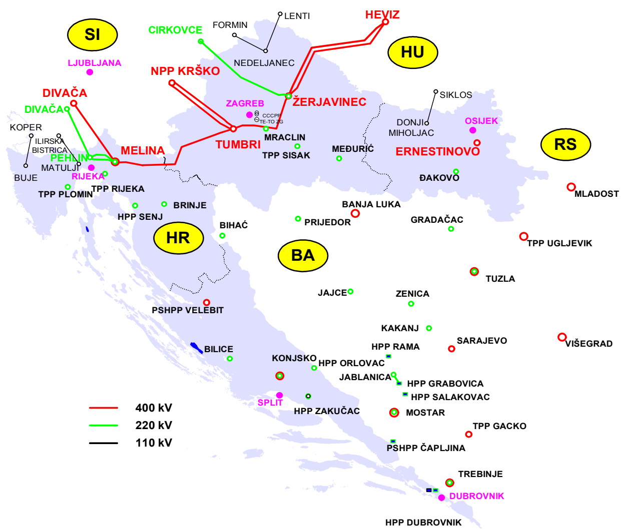

Fig. 1 Interconnection lines at the interface between Croatian power system and UCTE

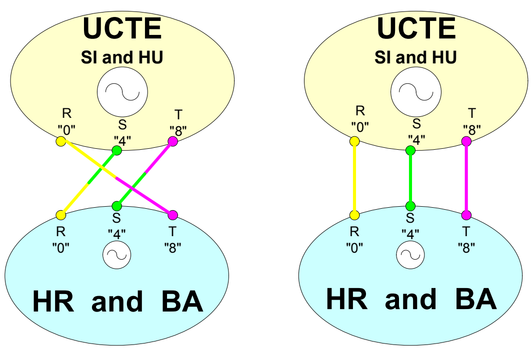

Fig. 2 Schematic diagram of the phase sequence at the Croatia – UCTE interface before (left) and after (right) arranging the phase sequence

2. System Operation Requirements And Dynamic Simulation

The dynamic simulation scenario involved separation and islanding of power systems of Croatia and BiH after disconnection of the 400 kV tie line Žerjavinec (HR) – Hévíz (HU) 2, and their resynchronisation to UCTE via the 400 kV line Tumbri (HR) – Krško (SI) 1. This simulation was performed in order to provide answers to the following questions: (i) will the system be stable in this scenario and (ii) how long would the island operation last. Initial power system configuration and steady state were defined according to the planned basic scenario with total consumption of 2750 MW and 50 MW surplus generation in power systems of Croatia and BiH. All generating units with capability of primary frequency regulation in these two systems were requested to be in the frequency sensitive mode of operation and total primary regulation reserve was kept at approximately 250 MW. Further, load-frequency control was performed by Croatian power system, in pure frequency control mode and with secondary regulation reserve of 200 MW and frequency bias set to 400 MW/Hz.

The initial phase relations between corresponding phases in UCTE and Croatian systems were such that there was a nominal phase lag of 120° in Croatian / BiH systems (phase R corresponding to phase S in UCTE, see Fig. 2). The initial phase lag of the voltage phasor at 400 kV node S/S Tumbri (HR) behind the voltage at 400 kV node Krško (SI/UCTE) in the planned steady state was expected to be around 100°. In order to reach synchronisation conditions it was therefore necessary to have Croatian and BiH systems accelerated during islanding, hence the requirement for the 50 MW surplus generation in the island. Parameter settings of the synchro-check relay at Tumbri substation (Δf=100mHz, $\Delta\delta$=10° and ΔU=40kV) have been determined on basis of experience and were used as the actual synchronisation criteria in the simulation model.

The power system dynamic model comprised a detailed power system models of Croatia and Bosnia ("interior system") at 400, 220 and 110 kV level, Slovenia at 400, 220 and partly 110 kV with Austria, Hungary, North Italy, Czech Republic and Slovakia at 400 and 220 kV level and the rest of the UCTE represented by dynamic equivalents at the border of the modelled system. PSS/E power system simulator was used for simulations [4]. Basic model data for the initial state are given in Table I:

Table 1 Basic simulation model data

Simulation model data	HR+BiH	Total
Nodes	486	648
Nontransformer branches	531	754
Transformers	163	218
Machines, detailed model	50	30
Machines, classical model	-	18
Consumption, MW	2650	276171
Generation, MW	2755	276395

Synchronous machines in the "interior" model were represented by detailed fifth or sixth order models with saturation, including excitation systems, turbine governors and power system stabilisers where appropriate. Individual units and power plant equivalents in the rest of the model were also represented with detailed machine models and associated control systems with typical parameters. The large equivalents were modelled as classical machine models.

Modelling of the synchrocheck device at Tumbri substation was given particular attention. A suitable user model was developed within the simulation program in order to verify the assumed synchrocheck parameters.

Results of predictive simulation of the separation, islanding and resynchronisation scenario are shown in Fig.3. The preliminary results were rather encouraging, particularly regarding duration of islanding and system security with respect to angle stability.

3. Organization of Measurement

System dynamics was continuously monitored during final activities of the phase sequence arrangement at the interface of the power systems of Croatia and UCTE.
Monitoring and recording of Croatian system dynamicsduring planned activities was focused primarily to electromechanical transients in the frequency range 0.1-2 Hz. Requirements to measuring equipment and choice of measurements were specified on that basis. Since the phenomena under consideration have system-wide nature it was necessary to record the dynamics of the entire system, i.e. simultaneously at several key points in the system. In addition, the measurements have to be strictly synchronised. Wide area measurement system (WAMS) would have been a simple and elegant solution, but since no such system existed in Croatian system at a time, a different approach had to be adopted. Five measuring teams, equipped with suitable digital recorders, were located at several key plants in the system - 400/110 kV S/S Tumbri, 400/220/110 kV substations Melina and Konjsko, HPP Dubrovnik and CCCPP TE-TO Zagreb (test points TP-1 to TP-5 in Fig.4). These test points were chosen so as to capture the entire system dynamics as representatively as possible using available measuring equipment and staff. The chosen signals, mainly active power flows in transmission lines and bus frequencies and voltages, were taken from the existing measuring transducers installed in substations. Suitable multichannel digital recorders with depth of recording not less than 500 seconds at sample rate of 200-1000 samples per second were used at all measuring posts except HPP Dubrovnik and CCCPP TE-TO Zagreb.

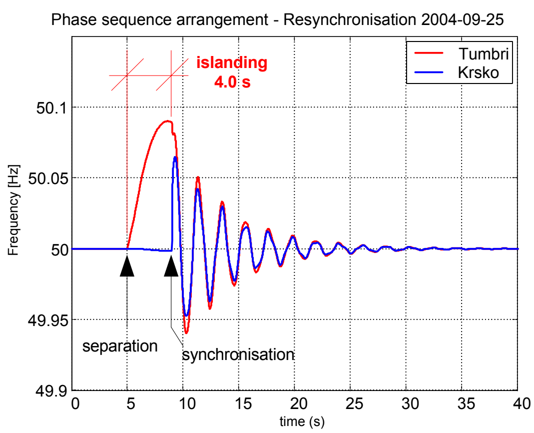

Fig. 3.1 Frequency at 400 kV nodes Tumbri (HR) and Krško (SI/UCTE)

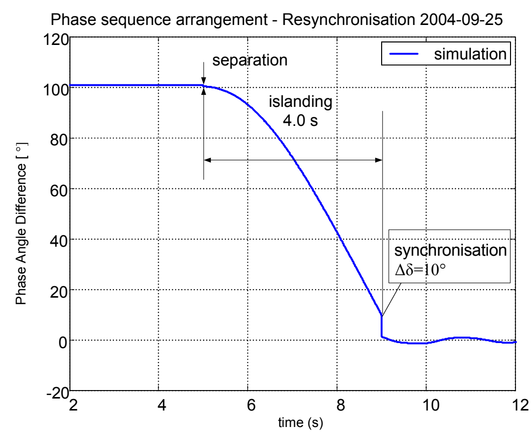

Fig. 3.2 Phase angle difference between voltages at 400 kV nodes Tumbri (HR) and Krško

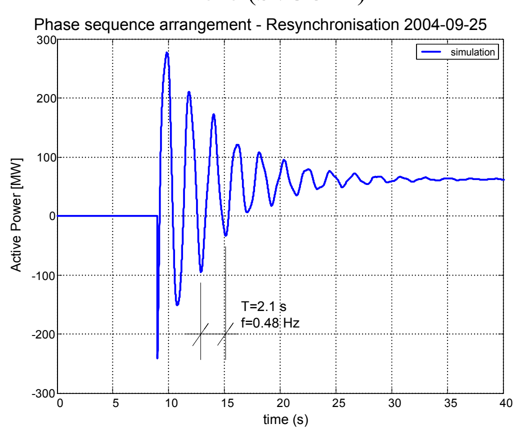

Fig. 3.3 Active power in 400 kV line Tumbri (HR)–Krško 1 (SI/UCTE)

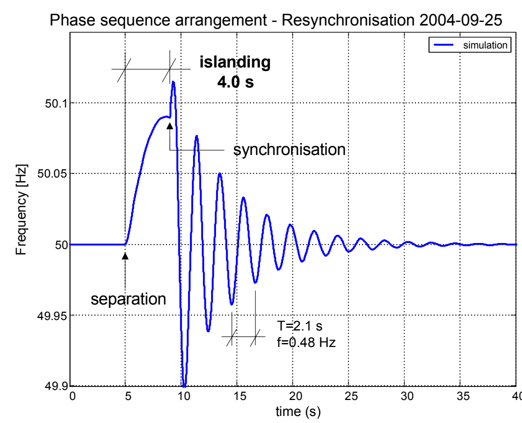

Fig.3.4 Frequency at 110 kV side of the unit 1 step-up transformer at HPP Dubrovnik

Figure 3 Separation of Croatia and BiH from UCTE, islanding and resynchronisation – simulation results

In these two power plants there are permanently installed disturbance recorders at generating unit level that are capable of recording instantaneous values of voltages and currents with sampling frequency of 2000 Hz. For our purpose it was only necessary to configure them so as to enable long enough recording duration.
Measurements were coordinated from the central coordination post at National Dispatching Centre in Zagreb . In rather short time that was available for preparation of the project it was not possible to establish a system of automatic synchronisation and starting of

measuring equipment. Luckily, the time scale of phenomena under consideration did not require high-speed triggering, so it was possible to rely on manual starting of recorders upon receiving order via voice phone communication, along with sufficient depth of storage of the digital recorders. Based on our previous experience with similar system-wide measuring schemes [1], [2], the following procedure was adopted.

(1) Before switching of each tie line an order to start recorders was issued from the central coordination post, simultaneously to all measuring teams.

(2) Synchronisation of measurements was achieved by adjusting internal clocks of all recording devices according to the exact time signal from precise automatically radio-controlled clocks available at each test post.

(3) Once the recording had started, each measuring team was responsible for storing and archiving the recorded signals

(4) For each case of switching an interconnection line at the Croatia – UCTE interface, two steady state snapshots were taken from the SCADA-based dispatcher analysis package (DAM) running at NDC Zagreb, one immediately before the switching and the other after settling of transients, i.e. upon reaching a new quasi steady state. Besides for archiving purposes, those snapshots were also used to check dynamics recordings and for establishing initial load flow cases for dynamic simulations.

(5) Information about exact times of switching was taken later from sequence-of-event (SOE) recorders. Records from different measuring posts were precisely time-aligned using that information.

4. Measurement And Simulation Of Croatian Power System Dynamics

Dynamics of Croatian power system was recorded and subsequently simulated for the following events:

- switching off of the 220 kV tie line Pehlin (HR) – Divača (SI)
- switching off of the 400 kV tie line Melina (HR) – Divača (SI)
- complete separation of power systems of Croatia and BiH from UCTE by switching off the last remaining 400 kV tie line Žerjavinec (HR) – Hévíz (HU), followed by island operation of Croatia and BiH and their resynchronisation to UCTE via the 400 kV tie line Tumbri (HR) – Krško 1 (SI)
- switching on of the 400 kV tie line Tumbri – Krško 2
- switching on of the 220 kV tie line Žerjavinec (HR) – Cirkovce (SI)
- switching on of the 220 kV tie line Pehlin – Divača
- switching on of the double circuit 400 kV line Žerjavinec (HR) – Hévíz (HU)

Measurement and simulation results are shown and discussed here for two selected cases. Time domain responses of representative variables are shown simultaneously in the geographical representation of Croatian 400 and 220 transmission network, along with initial power flows in important transmission lines (individual graphs denoted as subfigures, e.g. subfigure Fig. 4.1 in Figure 4).

4.1 Croatian Power System Dynamics During Separation from UCTE, Islanding and Resynchronisation Of Croatian And BiH systems

The central and the most complex activity of the phase sequence arrangement project was the aforementioned separation of power systems of Croatia and BiH from UCTE system, followed by their islanding and resynchronisation to UCTE. The expert team at Tumbri substation, directly responsible for synchronisation, was permanently in direct phone contact with the team and station operator at Žerjavinec substation. In that way it was possible to start synchronisation and switch on the 400 kV line Tumbri – Krško 1 immediately after having received the information that the 400 kV line Žerjavinec – Hévíz had been switched off. According to expectations, the resynchronisation was successfully done as soon as the synchronisation conditions set in the synchro-check relay (Δf=100 mHz, $\Delta\delta$=10° and ΔU=40 kV) had been met for the first time. Owing to well-planned operational state of the system and careful execution of the procedure, duration of the island operation of Croatian and BiH power system was only 4.49 seconds which is very close to the estimated duration of islanding obtained from predictive simulations (4.0 seconds).

Measured and simulated time domain responses of representative variables in Croatian power system are shown in Fig.4. Initial steady state in the simulation was adjusted according to the snapshot of the system steady state taken from DAM software immediately before the separation. Power flow on line Žerjavinec – Hévíz was about 65 MW towards Hévíz which was close enough to the desired 50 MW surplus generation.

Because of that surplus generation, Croatian and BiH system were accelerating during island operation and the frequency was increasing (see the frequency signal recorded at 400 kV node Tumbri in subfigure.Fig. 4.1). At the instant of synchronisation the frequency deviation was 75 mHz (80 mHz in simulation) above the initial value. As can be seen from the active power in 400 kV line Tumbri – Krško (Fig. 4.4), oscillations of Croatia and BiH against UCTE were well damped with dominant frequency of 0.48 Hz (from both simulation and measurement). However, damping of that oscillations is lower in simulation than in the real system.

In conclusion, there were no problems with angle stability during separation, islanding and resynchronisation, mainly owing to careful planning of initial operational conditions and availability of practically complete internal transmission network in the Croatian and BiH systems.

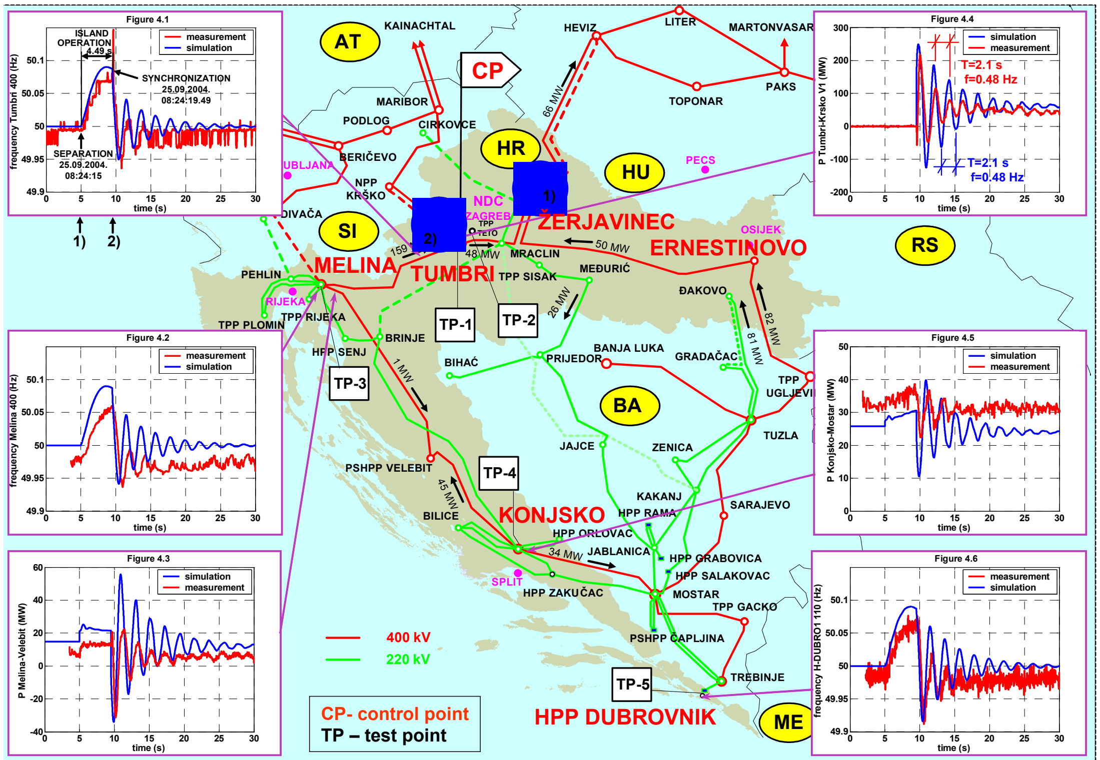

Figure 4 Croatian 400 and 220 kV transmission network with active power flows before separation of Croatia and BiH from UCTE (25 September 2004 at 08:24:15) and characteristic time domain responses during separation, islanding and reconnection (**red - measurement, blue – simulation)**

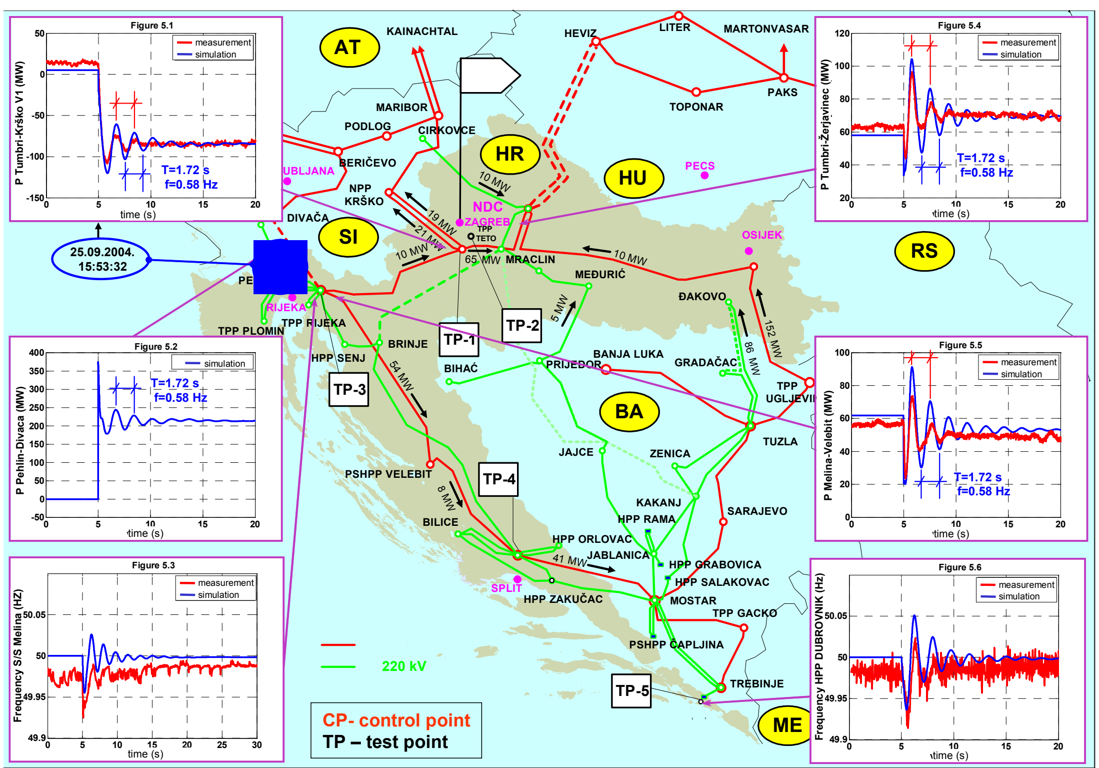

Figure 5 Diagram of Croatian 400 and 220 kV transmission network with active power flows before reconnection of the 220 kV line Pehlin – Divača (on 25 September 2004 at 15:53:32) and time domain responses of representative variables **(red - measurement, blue – simulation)** following reconnection of that line

4.2 Croatian Power System Dynamics Following Switching On Of The 220 kV Tie Line Pehlin – Divača

By switching on the 220 kV tie line Pehlin (HR) – Divača (SI), the loop between Slovenian and Croatian power systems (Krško - Tumbri - Melina / Pehlin – Divača - Beričevo /Kleče – Podlog - Maribor/Cirkovce – Krško) became closed, which caused redistribution of power flows from Rijeka to Zagreb region (see Fig.5). After closing the loop there was a power flow of 254 MW from Pehlin to Divača, while the power flow in the 400 kV line Tumbri – Melina decreased from around 210 to 38 MW, while the power flow in the 400 kV line Tumbri – Krško reversed from cca 40 (2x20) MW towards Krško to 160 (2x80) MW towards Tumbri and power flow from Cirkovce to Žerjavinec increased from 10 to 54 MW (all values taken from DAM).
Inspection of time domain responses in Fig. 5 shows that the electromechanical oscillations of Croatian and BiH system against UCTE with characteristic frequency of 0.53 Hz (0.57 Hz in simulation) were again well-damped (see Fig. 5.1, 5.2, 5.4 and 5.5). The frequency was slightly increased, mainly due to increased strength („stiffness“) of the connection between systems of Croatia+BiH and UCTE. In this case, too, simulation results are in rather good agreement with measurements but the damping in simulation is again worse than in reality. In conclusion, dynamic behaviour of the system in this case was good and the system security with respect to angle stability was preserved.

5. Conclusion

One of the most important events in recent history of European interconnection was the reconnection of the two synchronous zones of 10th October 2004. Particularly challenging task in preparation of the reconnection was arranging phase sequence at the interface between Croatia and UCTE because it involved separation of power systems of Croatia and BiH from the UCTE grid, their island operation and resynchronisation. The unique opportunity to record power system dynamics in such special circumstances was fully exploited.
Two dominant modes of interarea oscillations have been observed, one of them characteristic for power systems of Croatia and BiH, and the other attributable to a coherent group of power systems in the north-eastern part of UCTE. Frequency of the characteristic HR+BiH mode was lying in the range from 0.5 to 0.8 Hz, depending mainly on strength of the connection between Croatia and UCTE, i.e. on number of tie lines in operation.
Security of power systems of Croatia and BiH with respect to angle stability was preserved, mainly owing to careful planning, favourable initial system state, precise execution of all procedures and practically completely available internal transmission network. However, under less favourable conditions, particularly with some important elements of the internal network out of operation, the problems with stability of the Croatia-BiH interarea mode could be expected. It is therefore necessary to have all power system stabilizers on generating units in Croatia and BiH active and properly tuned for effective damping of electromechanical modes with frequencies ranging from 0.1 to 0.8 Hz. Dedicated field tests and dynamic simulation studies related to damping of interarea oscillations in Croatian power system should be systematically performed. Importance of Croatian and Slovenian power system as key links in the power transfer corridor from north-eastern part of UCTE to its south-west (i.e. to North Italy) has been confirmed.
Simulation prediction of system dynamic behaviour during separation of Croatian and BiH power systems from UCTE, their islanding and reconnection proved to be reliable and the simulation results were of great help in predicting risks involved with complex activities of the phase sequence arrangement project. However, comparison with measurements has shown that the dynamic model of the internal Croatian-BiH system should be refined and that of the external UCTE system must be thoroughly revised.
The proposed measuring and recording scheme was successfully applied for capturing system-wide dynamics but it is no substitute for a proper wide-area measurement system (WAMS). In the meantime Croatian electricity utility (HEP) has started a WAMS development project that will include the two already existing phasor measurement units (PMUs) in 400 kV substations Žerjavinec and Tumbri and will be finally included into UCTE WAMS.

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