Analysis Of Croatian Power System Dynamic Response In Case Of Switching The 400 kV Line Tumbri - Hévíz In Real System

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ABSTRACT:. The paper presents field test and simulation results of the dynamic behaviour of the Croatian power system following switching off and on of the 400 kV line Tumbri - Héviz. This interconnection line between Croatia and Hungary has major impact to the operation of the Croatian power system. Power flow on it is usually 500 to 1000 MW in the north-east to south-west direction. Results of preliminary dynamic stability studies of Croatian power systems pointed at potential risk of inadequate stability margins, hence it was felt necessary to verify the simulation results by comparison with field test results.

Suitable tests were performed when the above mentioned 400 kV line had been switched off for maintenance purposes. Four test teams were engaged: three of them at the major 400 kV substations in Croatian power system and one at the National Dispatching Center in Zagreb from where the whole operation was coordinated. Active power flows on selected transmission lines and power frequency were recorded by suitable digital equipment. Steady state of the Croatian and neighbouring power systems immediately before and after the line switching was captured in close collaboration with operators in regional dispatching centers and in neighbouring countries.

Prony analysis of the test results yielded characteristic interarea modes of oscillations observable in the Croatian power system. In comparison with simulation results the measured dynamic responses are better damped which calls for further refinement of simulation models.

Keywords: electric power system, electromechanical transients, measurement, Prony analysis, simulation

I INTRODUCTION

Analysis of electric power systems dynamics is today mainly performed by use of simulation models, often based on some assumed future network configurations and steady states and uncertain model parameters. Comparison of simulation results with recordings from real system for purpose of model validation is of utmost importance as it is usually the only way to properly verify the model response.

Under the increasing pressure to better utilize system resources the dynamic security assesment is becoming very important in power system operation. It is now growing practice in the industry to have installed dedicated recording equipment at strategically located points in the system in order to permanently monitor the system behaviour and to issue early warning if the system safety margin falls below certain acceptable level [1]. In the Croatian power system there is no such monitoring scheme. In its present state and with the power system of Bosnia and Herzegovina not yet fully restored the Croatian system has an essentialy longitudinal shape with significant amount of hydro generation concetrated in its southern region of Dalmatia (see Fig.1). Stability problems have been observed many times in the past decade, particularly in certain operating regimes characterized by favourable hydrology and large power transfer from south to northwest. Occasionally, these problems are still present, but neither systematic study of system dynamics nor dedicated system-wide tests aimed at determining dynamic characteristics of the system in its actual state have been performed until recently [2].

Outage of the 400 kV transmission line Hévíz – Tumbri, planned by the Hungarian electricity utility for April 2000 for maintenance purposes, was seen as an ideal opportunity to perform for the first time recording of dynamic behaviour of the Croatian power system in case of a major disturbance. On the initiative from Croatian electricity utility (HEP), precisely its System Operator, a set of tests was organized in which several test/measurement teams were engaged covering the three major 400 kV substations: 400/110 kV substation Tumbri, 400/220/110 kV substation Melina and 400/220/110 kV substation Konjsko (see Fig. 1).

Test results were analysed and compared to simulation results obtained from a standard time-domain simulation. The simulation model comprised detailed representation of the 400, 220 and 110 kV network in Croatian system, complete representation of 400 and 220 kV network in Slovenia (with partially equivalented 110 kV network), 400 and 220 kV network of Bosnia and Herzegovina (the part operating within the 1st UCTE synchronous zone) with detailed model of 110 kV network in its southern part, and equivalent representation of UCTE and CENTREL systems sufficient to represent their characteristic dynamic behaviour. In total the model comprised about 450 nodes and approximately 100 generators. Initial steady states were adjusted so as to be best fitted to actual system states (captured immediately before each switching operation).

Paper accepted for presentation at the 3rd Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion
MED POWER 2002, jointly organized by
National Technical University of Athens,
IEE Hellas, Israel and Cyprus,
Athens, Greece, November 4-6, 2002

II ORGANIZATION OF TESTS

Two tests were conducted: the first one was switching the 400 kV line Tumbri – Hévíz off on 5th April (P01) and the second was switching on that line (on April 6th, P02). Because of system-wide impact of these operations and interaction with neighbouring systems, and regarding the number of experts of different specialities involved in performing the tests, the whole endeavour obviously required very careful preparation and planning. Coordination between participants was given particular attention. An operational programme was elaborated specifying all relevant details concerning (i) test procedures at the three test points in the Croatian system (TP8 Tumbri, TP9 Melina and TP10 Konjsko), (ii) collecting steady-state data in Croatian system and neighbouring systems before and after the system transient, and (iii) details of coordination scheme and organization of the communication system.

The tests were carried out by expert teams from Energy Institute Zagreb, HEP (System operator), Faculty of Electrical Engineering in Zagreb and Končar-INEM, in collaboration with experts and operational staff in national dispatching centres (NDCs) of Slovenia, Hungary and Bosnia and Herzegovina.

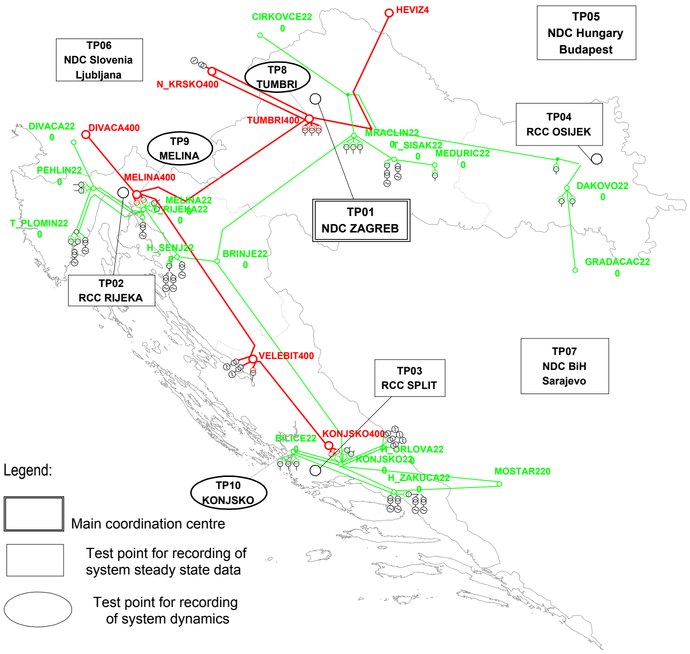

Figure 1 400 and 220 kV Croatian transmission network and disposition of test points (TP)

Basically, each test consisted of the following steps:

(i) quasi-simultaneous capturing of system configuration and steady-state (line power flows, bus voltages) in Croatian and neighbouring power systems (Hungary, Slovenia, Bosnia and Herzegovina); approximately two minutes before each switching operation (obtaining the closest possible approximation to a "snapshot" of the pre-disturbance steady-state of the system)

(ii) recording of dynamic response of characteristic quantities, during at least 160 seconds following the disturbance (i.e. the switching operation)

(iii) quasi-simultaneous capturing of transmission network configuration and steady-state values (line power flows, bus voltages) in Croatian and neighbouring power systems (Hungary, Slovenia, Bosnia and Herzegovina); approximately two minutes after each switching operation ("snapshot" of the post-disturbance steady-state)

Due to very short time available for preparation, signals from the existing measuring transducers were used for recording of system dynamics. While being aware that dedicated transducers would be better suited for this purpose, it was judged, on basis of their properties, that the existing transducers would be quite acceptable. In addition, one frequency transducer had been temporarily installed in substation Konjsko because the largest frequency excursions was expected to occur there.

Operating personnel at regional dispatching centres (RDCs) in Croatia (i.e. RDCs Rijeka, Osijek and Split), in the NDCs of the neighbouring systems (Ljubljana, Budapest, Sarajevo) and staff in the Croatian NDC in Zagreb were involved in recording steady-state data. Strictly speaking, those system state "snapshots" were not exactly simultaneous because it was not possible at the time, given the technical limitations of the existing equipment at dispatching centres, to get true "snapshots" of system state at the moment when appropriate command was issued by the main test coordinator. Instead, screen reports have been stored and subsequently printed out. Steady-state data for Croatian system have also been supplemented by the results of steady-state estimator at the NDC Zagreb.

Time responses of active power flows and frequency have been recorded during the transient periods following the switching operations. Digital recording equipment was used: transient recorder ABB Goertz SE560/561 (at Tumbri), oscilloscope LeCroy 9304AM (at Melina) and PC-based data acquisition system WaveBook (at Konjsko). Manual triggering upon a command issued by the test coordinator was applied.

III ANALYSIS OF TEST RESULTS

A Method of Analysis

Recorded time-domain response of N selected measured quantities (recorded signals $y_l(t)$, l=1,2..N) represent complex system motion resulting from the interaction between individual generating units, groups of units and system areas. Prony analysis [3] has been performed on a carefully chosen segment of each recorded signal (see Figs 2 and 4, left) taken as input signal. In this process an equivalent linear system is identified from each (l-th) input signal $y_l(t)$, its order and parameters being determined so that its response $y_{rl}(t)$ is fitted to original input signal $y_l(t)$ with desired accuracy in the least squares sense. Quality of identification (index of match between the original signals and the equivalent system responses) is expressed in terms of signal-to-noise ratio (SNR).

The substitute response $y_{rl}(t)$ is a sum of M simple oscillatory and aperiodic *real* time-domain responses, or signal components $y_{rl,m}(t)$, $m=1,2..M$. Each of them is determined by eigenvalues of the linear system and by its initial amplitude and phase, also obtained from Prony analysis. Note that *m*-th oscillatory signal component corresponds to a pair of complex eigenvalues $\lambda_{i,i+1}=\alpha_m \pm j\omega_m$, while an aperiodic component corresponds to a single real eigenvalue $\lambda_i=\alpha_m$.

Since the identified modal content could contain components of little or no interest, the next step is to determine the most significant modes identified from each signal. This could be done by computing "signal strengths" W_m of individual components, proportional to signal energy:

$$W_m = \int_{t_0}^{\infty} \left[y_{rl,m}(t) \right]^2 dt \qquad (1)$$

where $y_{rl,m}(t)$ is the *m*-th component of signal *l,* corresponding to a mode *m* with positive damping ($\zeta>0$). It is now possible to define relative strengths with respect to the "strongest" component, then to order components by decreasing relative strengths and finally to reject those with strengths below some predetermined threshold (e.g. 5%). The eigenvalues (modes) that correspond to the retained signal components are then considered dominant in the given signal.

Since input signals are analysed individually, certain dispersion of identified modes, caused by varying quality of input signals, should be expected. To avoid that problem completely, it would be necessary to analyse all the recorded signals simultaneously, treating them as a response of a multi-output system. however, that would require much larger number of inputs (measurements) than it was available in this case. Better input signal quality (e.g. achieved by using dedicated measuring transducers) would also enhance the quality of identification.

B Presentation of Results

Results of measurement and time-domain simulation using non-linear power system model, as well as Prony analysis results, are shown in two figures for each case (P01 and P02). Measured and simulated time-domain responses of active power flows on the selected 400 and 220 kV transmission lines and frequency deviation at the 400 kV node Konjsko are shown simultaneously in the first figure. Segments of measured signals taken as inputs for Prony analysis (in duration of 8 seconds) are indicated by bold line. Signal-to-noise ratio indicating quality of Prony estimate and initial (pre-disturbance) values of power flows are also shown for each measured signal.

Prony analysis results are given in the next figure. Significant identified modes (eigenvalues) are shown on the left in the complex plane (note that only the fourth quadrant is shown for sake of clarity, i.e. oscillatory modes corresponding to complex pairs of eigenvalues are represented only by the eigenvalues with positive imaginary part). Due to dispersion of identification results groups of modes will occur instead of clearly defined individual modes. Such groups are here enclosed in circles with approximate average frequency and damping ratio indicated above the line. Modal contents of input signals represented by a bar-graph showing relative strengths of modal components in each measured signal is shown on the right side of the same figure. Each group of bars represents strengths of dominant modes in one input signal. Height of each bar is proportional to the relative strength of a component expressed in percentage of the strength of the dominant component in that group. Up to five most significant components per signal are shown, provided their relative strengths are at least equal to 5%. Natural frequency f_0 and damping ratio ζ of the modal component are also shown above each bar.

C Dynamic Behaviour of Croatian Power System Following Switching the 400 kV Line Tumbri-Hévíz Off (Case P01)

The 400 kV interconnection line Tumbri – Hévíz was switched off on April 5th, 2000 at 7:20. Immediately before the switching there was approximately 260 MW flowing on that line in the direction from Heviz (Hungary) to Tumbri (Croatia). Croatian power system was in its normal configuration with all 400 and 220 kV lines in operation. Around 140 MW was flowing from the 220 kV node Gradačac (BiH) to the 220 kV node Đakovo (Croatia).

Measured and simulated time-domain responses of active power flows on the selected 400 and 220 kV transmission lines, and of frequency deviation at Konjsko, are shown together in fig. 2. Compared to simulation (left), real system responses (right) are characterized by much better damping and somewhat lower frequency of the dominant mode oscillations. It can be seen, too, that the pre-disturbance power flows from the model differ from those measured in the real system. These differences are mainly caused by simplifications in the model of BiH system used at the time. In spite of the shortcomings of the model, the simulation results were found quite useful in preparation of tests.

Prony analysis results are given in figure 3. Quality of identification was quite good with SNR exceeding 30 dB in the worst case. Even better quality (SNR over 40 dB) has been achieved for the signals in which there was a clearly recognizable dominant oscillatory mode (see fig.2, left).

The encircled group in fig. 3 (left) represents the interarea mode (0.63 Hz) of the southern part of power systems of Croatia and BiH, which is clearly dominant in the power flows on the lines incident with the substation Konjsko (Konjsko-Mostar, Konjsko-Velebit, Konjsko-Brinje) and on the 400 kV line Melina – Divača. In power flows on lines Konjsko-Velebit and Brinje-Konjsko there is a weakly damped 0.33 Hz mode, also observable in the power flow on line Tumbri-Krško. Considering accuracy and resolution of measurement, accuracy of identification in case of the dominant interarea mode is quite acceptable. Low-frequency UCTE /CENTREL modes [4] can also be observed, but due to limited quality of measurements they could not have been identified with better accuracy.

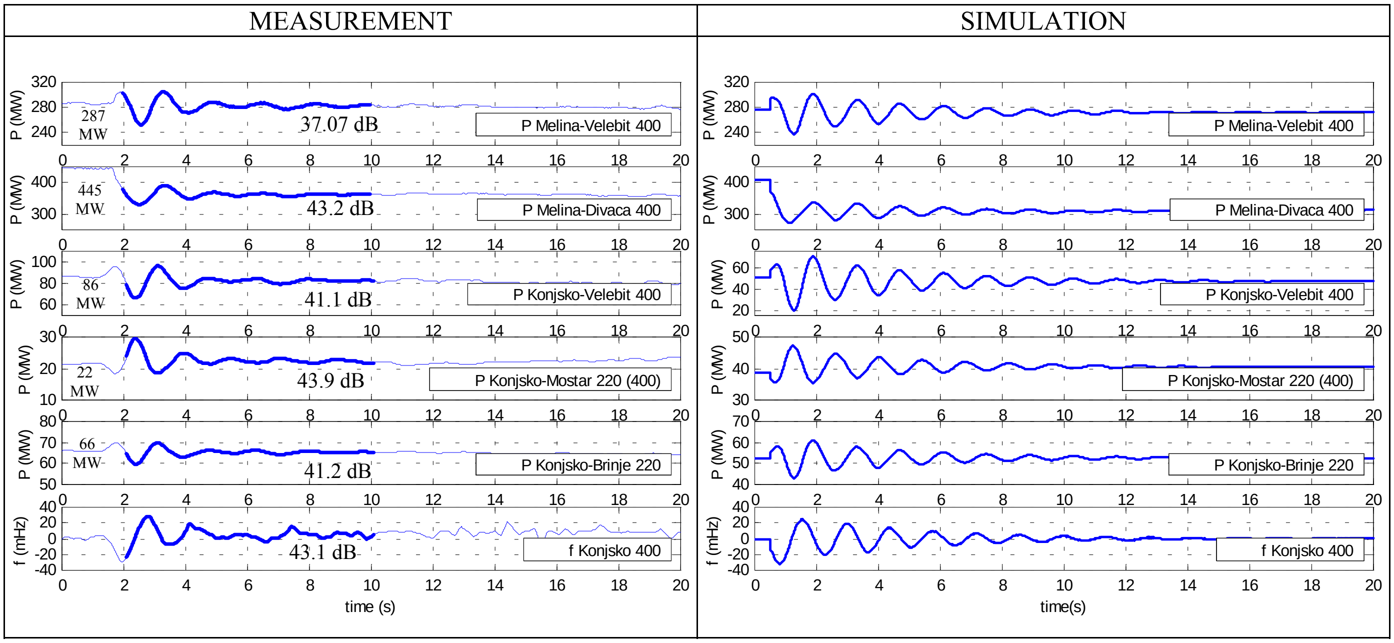

Figure 2 Measured (left) and simulated (right) time-domain responses of active power flows on transmission lines and frequency deviation at 400 kV node Konjsko upon switching off the 400 kV line Tumbri – Hévíz (case P01)

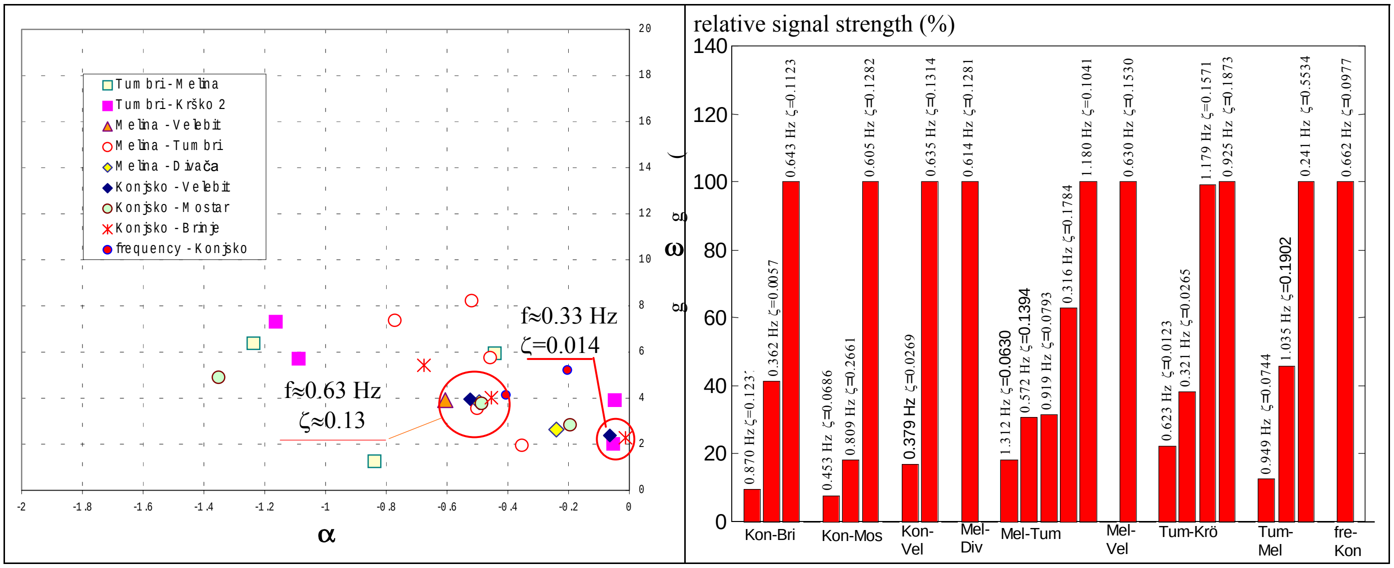

Figure 3 Results of Prony analysis of measured active power flow responses upon switching off the 400 kV line Tumbri – Heviz (P01) complex-plane representation of significant modes (left) and signal components strengths (right)

Dynamic behaviour of Croatian power system upon switching off of the 400 kV line Tumbri-Hévíz with initial flow of 260 MW is stable and well-damped. The pre-disturbance system state was rather favourable from stability point of view. For illustraton of the disturbance intensity, maximum amplitude of frequency deviation at Konjsko was approximately 60 mHz$_{pp}$ (peak-to-peak), maximum amplitude of power swing in the 400 kV line Melina – Velebit about 55 MW$_{pp}$ and on the 400 kV line Melina – Divača about 50 MW$_{pp}$ (see fig. 2).

D Dynamic Behaviour of Croatian Power System Upon Switching On of the 400 kV Line Tumbri-Hévíz (P02)

The 400 kV interconnection line Tumbri – Hévíz was switched on again on April 6th 2000 at 22:00. Croatian power system was again in its normal configuration with all 400 and 220 kV lines in operation. Immediately before the switching there was approximately 145 MW flowing from BiH to 220 kV node Đakovo via the 220 kV line Gradačac – Đakovo (see fig. 1).

Responses of active power flows on lines and of frequency deviation at 400 kV node Konjsko to the disturbance caused by switching on the line are shown in fig. 4.

Dynamic behaviour of Croatian power system is stable though not so well damped as in the first test. Settling time was approximately 12 seconds. Maximum amplitude of active power flow deviation was 120 $\mathrm{MW_{pp}}$ on 400 kV line Melina – Velebit and 90 $\mathrm{MW_{pp}}$ on 400 kV line Melina – Divača. Maximum amplitude of the frequency deviation at Konjsko was 126 $\mathrm{mHz_{pp}}$. Power flow on the line Tumbri-Heviz in the post-disturbance steady state was approximately 330 MW.

Prony analysis results are shown in fig. 5. Quality of identification is again high (SNR in dB in Fig.4 - left). Dominant interarea oscillations, already discernible from time-domain responses (fig. 4), are confirmed by modal contents of the signals (fig. 5, right). Frequency of the dominant-mode oscillations is somewhat higher (0.65 Hz) and damping ratio is lower than in the previous test (P01). This was according to expectations because the connection of the southern hydro generators to the UCTE is "tighter" when the 400 kV line Tumbri-Hévíz is in operation. One UCTE/CENTREL mode (0.28 Hz) is clearly observable.

Simulation results agree pretty good with measurements but are conservative, with higher oscillation frequency and lower damping of the dominant interarea mode than in the real system. Obviously, the simulation model need to be further improved, in particular the model of the BiH power system.

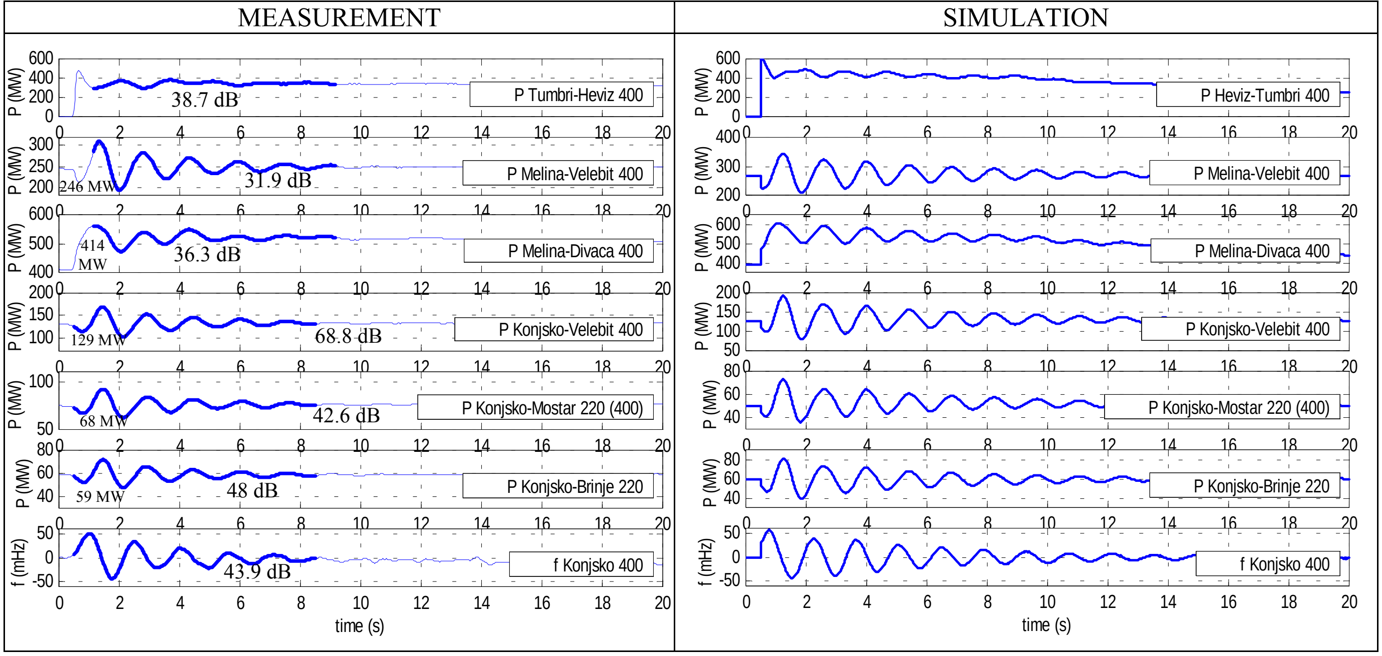

Figure 4 Measured (left) and simulated (right) time-domain responses of active power flows on transmission lines and frequency deviation at 400 kV node Konjsko upon switching on the 400 kV line Tumbri – Hévíz (P02)

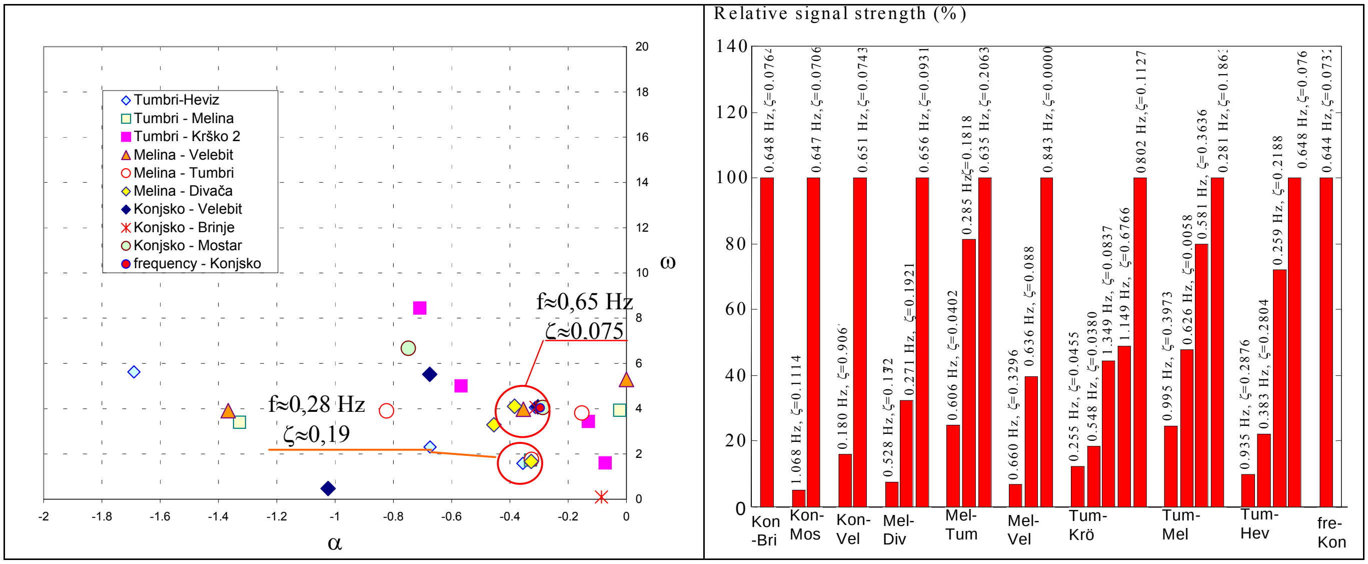

Figure 5 Results of Prony analysis of measured active power flow responses upon switching on the 400 kV line Tumbri – Heviz (**P02**); complex-plane representation of significant modes (left) and signal components strengths (right)

IV CONCLUSION

First-ever system-wide tests, aimed at determining dynamic properties of Croatian power system in its present state, were conducted in April 2000, and their results gave invaluable insight into the matter.

The dominant interarea oscillatory mode in Croatian power system has natural frequency ranging from 0.6 to 0.7 Hz. It represents coherent motion of hydro machines in the southern part of Croatian and BiH power system with respect to the rest of the system and can be clearly identified from the measured responses of power flows observed on selected 400 and 220 kV lines. As expected, this mode was better damped and had slightly lower frequency in case of switching off the 400 kV tie line Tumbri-Hévíz (P01) as compared to the case of switching that line on (P02): "stiffness" of the electrical connection of the southern group of hydro units to the UCTE interconnection is increased when the above mentioned 400 kV line is in operation. In both cases the damping of that mode was acceptable (damping ratio over 0.05). Note, however, that the pre-disturbance steady state of Croatian system was rather favourable with respect to stability (no large power transfers from the south) but, on the other hand, the power system of BiH was not fully restored at the time.

Lower-frequency UCTE/CENTREL modes have been also observed, but they could not have been identified more accurately given the quality of recorded responses.

Results of power system dynamics simulations performed prior to tests were validated against actual system responses showing rather good match. Generally, the non-linear power system model used for simulation gives more conservative results, i.e. lower damping of the critical interarea mode. It was concluded that details of the model, particularly of the power system of Bosnia and Herzegovina, should be carefully examined, completed and updated in order to achieve better prediction of system behaviour.

In conclusion, benefits of such tests, e.g. better knowing and understanding system behaviour, refinment and assessment of simulation models, etc., fully justify the effort. This kind of tests should be repeated from time to time. They can be succesfully prepared and conducted only in close mutual cooperation between neighbouring systems.

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VI BIOGRAPHIES

M. Stojsavljević was born in 1946 at Velika Popina, Croatia. He received his B.S. and M.S. degrees from Faculty of Electrical Engineering, University of Zagreb, in 1969 and 1980 respectively. In 1969 he was employed by Electrotechnical Institute "Rade Končar" in Control Systems Division. He participated in numerous projects in the field of power system stability and control, e.g. dynamic stability enhancement of power system of former Yugoslavia in parallel operation with UCPTE (1973). From 1984 to 1991, he was the manager of Power plants and systems division.

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