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Monitoring of Power System Dynamics during Reconnection of 1st and 2nd UCTE Synchronous Zones

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SUMMARY

Reconnection of the 1st and the 2nd UCTE synchronous zones on 10th of October 2004 was not only a major event but also a technically very challenging task for all involved. Activities were coordinated by the UCTE Executive Team from the National Dispatching Centre (NDC) in Zagreb (Croatia). During the reconnection, power system dynamics was permanently monitored at the NDC in Zagreb using UCTE WAMS and Croatian system dynamics was monitored through a manually coordinated wide area measuring scheme (further: "HR-WAMS") specially arranged for this occasion. Bus voltage frequencies and phasor angles representing dynamics of the 1st zone (at Mettlen, Switzerland) and the 2nd zone (at Ag. Stefanos, Greece) were observed through UCTE WAMS while relevant quantities at key substations in Croatian power system were monitored through HR-WAMS. System dynamics was monitored and recorded during synchronisation of the two zones (switching on of the 400 kV interconnection line Sandorfalva (H) – Arad (RO)) as well as during reconnection of all other 400 kV tie lines between the two zones. A new lightly damped interarea mode with the period of about 4-5 seconds was observed after the reconnection, propagating through the Croatian power system and further into the UCTE system via the 400 kV line Melina (HR) – Divača (SI).

Detailed analysis of the measurements taken during reconnection, as well as analysis of some later recordings of spontaneously arising oscillations, has shown that there could be problems with the newly introduced interarea modes. Another aspect of interest is the use of WAMS measurements for validation of power system models. On this occasion simulation was done for the case of synchronisation of the two zones. The power system model included detailed representation of power systems of Croatia (HR) and Bosnia and Herzegovina (BiH) and appropriate dynamic models of the UCTE. Rather good match between simulation and measurement was achieved for the bus frequency at the 400 kV node Ernestinovo which represents the 1st zone dynamics, and for the bus frequencies at the 400 kV nodes Mladost (SCG) and Ag. Stefanos (GR) which represent the 2nd zone dynamics. These results are encouraging and WAMS measurements proved to be extremely useful in validation of the dynamic model while there is still much work to be done.

KEYWORDS

UCTE reconnection, WAMS, interearea oscillations, dynamic model validation

1. INTRODUCTION

Electromechanical interactions between groups of synchronous machines in large interconnected electric power systems are usually of very complex nature. They often result in oscillations around the operating point which arise due to various disturbances or to structural changes in the network. In absence of large disturbances those essentially nonlinear interactions and relationships can be described in terms of linearised differential equations and are referred to as small-signal angle stability. Frequency and damping of the oscillations are constantly changing as they depend on many factors such as network topology, machine parameters, loading levels, power transfers and so on. However, by using suitable analytical and measuring techniques it is possible to investigate inherent dynamic properties of a given power system in order to identify the most prominent modes of oscillations and to track and/or predict their changes during power system operation [3]. Today it is widely recognised that good knowledge and control of power system dynamics are increasingly important aspects of power system security, particularly when the systems are pushed close to their limits. Due to complexity of the problem it is not an easy task. The latest big step forward was introduction of WAMS technology that can be of great assistance in dealing with this problem by increasing the quality of monitoring and control of power system dynamics.

When interconnecting two large systems one could also reasonably expect the occurrence of new patterns of dynamic interactions, which in some cases may even lead to new, previously non-existing stability problems. It is known from our past experience that such stability problems may arise immediately after synchronisation of the two systems [1], and oscillations may be of such intensity that further parallel operation is not possible and special measures to enhance small signal stability margin are called for (e.g. installing properly tuned power system stabilisers at key machines).

Reconnection of the 1st and the 2nd UCTE synchronous zones was an example of interconnecting two large power systems (see Fig. 1). In autumn 1991 the European electric power system (UCPTE – Union for the Coordination of Production and Transmission of Electricity) was split into two synchronous zones due to devastation of transmission plants during war operations in Croatia and BiH. At that moment the first zone consisted of major part of the UCPTE (Austria, Belgium, one part of BiH, Croatia, France, Italy, Luxembourg, the Netherlands, Germany, Portugal, Slovenia, Spain and Switzerland) while the second zone comprised the power systems of Albania, the other part of BiH, Greece, Macedonia and Serbia and Montenegro. In the following years the first zone included also the power systems of Hungary, Czech Republic, Slovakia and Poland (since 1995), Algeria, Morocco and Tunisia (since 1997) and west Ukraine (so called Burshtyn Island, since 2002), and the entire power system of Bosnia and Herzegovina (since September 2004). In the meantime the power systems of Romania and Bulgaria have become part of the second synchronous zone (in 1993).

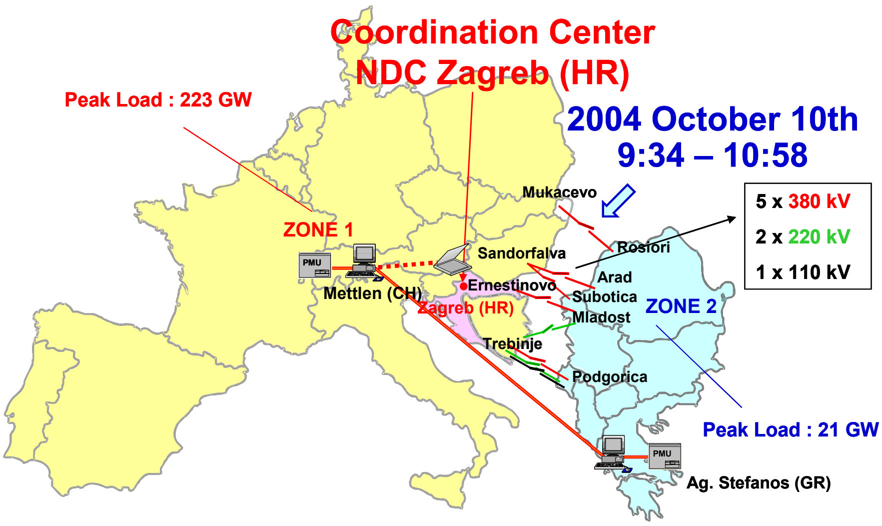

Figure 1 Reconnection of the 1st and 2nd UCTE zones

UCTE decided to start activities on preparing the reconnection of the two UCTE zones. The Executive team responsible for the project was established on 12 March 2002 and after the meticulous preparation the synchronisation and interconnection of the two systems took place on 10 October 2004. Necessary technical prerequisites for this were restoration of the pre-war transmission systems in Croatia and in Bosnia and Herzegovina, along with some important network reinforcements (e.g. 400/220/110 kV S/S Žerjavinec, 400/110 S/S Ernestinovo, 400 kV OHL Žerjavinec (HR) – Hévíz (H)) and phase sequence arrangement in Croatian and BiH systems with that in UCTE [5]. The Croatian electricity utility (Hrvatska elektroprivreda – HEP) played a very active leading role in the executive team. The final act of resynchronisation and interconnection was coordinated and monitored from the National Dispatching Centre in Zagreb, Croatia, by the team of UCTE experts. The reconnection at 400 kV level was done at five interconnection lines (see Fig.1), starting with synchronisation of the two systems at the line Sandorfalva (H) – Arad (RO) and followed by connection of lines Sandorfalva (H) – Subotica (SCG), Trebinje (BiH) – Podgorica (SCG), Mukachevo (wUA) – Rosiori (RO) and Ernestinovo (HR) – Mladost (SCG). It was completed in less than one hour (9:33AM to 10:25AM).

2. GOALS OF WIDE AREA MEASURING DURING RECONNECTION

Monitoring of system dynamics during reconnection of the 1st and 2nd UCTE synchronous zones was motivated by the following requirements:

- in general, monitoring of power system dynamics during switching of all interconnection lines between the two zones
- particularly, permanent monitoring at the coordination centre (NDC Zagreb) of angle dynamics between bus voltage phasors which are representative for motion of the two synchronous zones in order to early recognize potential stability problems (UCTE WAMS)
- monitoring of frequency dynamics of the two zones at their interface in Croatian system (at S/S Ernestinovo (HR) and Mladost (SCG)) during synchronisation
- monitoring of active power flows at the interface between Croatian power system and the rest of UCTE (HR-SLO: S/S Tumbri, S/S Melina; HR-H: S/S Žerjavinec; HR-SCG: S/S Ernestinovo and HR-BiH: S/S Konjsko)
- identification of interarea oscillation modes observable in dynamic responses of relevant quantities in Croatian system
- dynamic model validation.

The above requirements could have been fulfilled only by means of a wide area monitoring scheme. On-line monitoring of large-scale power system dynamics requires simultaneous measurements across a wide geographical area. Those measurements should be synchronised to a common time base and transmitted in real time to a concentrating point where they are further processed.

Measurements from UCTE WAMS were used for that purpose along with measurements from Croatian system ("HR-WAMS") as will be described below.

3. UCTE WAMS AT THE COORDINATION CENTRE IN ZAGREB

Existing UCTE WAMS consists of more than thirty PMUs located all across the Europe. Permanent monitoring of bus voltage phasors at two nodes representative for the 1st zone (Mettlen, CH) and the 2nd zone (Ag. Stefanos, GR) was arranged at the coordination centre in NDC Zagreb for purpose of system dynamics monitoring during reconnection (see Fig. 1). Bus frequencies and voltage phase angle difference (Mettlen – Ag. Stefanos) as a stability indicator were displayed on-line on a UCTE working station at the coordination centre in Zagreb [6].

4. WIDE AREA MEASURING SCHEME IN CROATIAN SYSTEM - "HR WAMS"

Present implementation of WAMS in Croatia (in operation since 2004) consists of two PMUs, installed at two geographically close 400 kV S/S Tumbri and Žerjavinec in the north-western part of the country (see Fig.2), and a system monitoring centre at HEP headquarters in Zagreb. Its primary purpose is monitoring of line loading and voltage stability along the important 400 kV transmission path. Obviously, the actual WAMS scheme covers only a small part of the Croatian power system and in this phase of development does not enable true system-wide monitoring of the entire national transmission network.

For purpose of wide-area monitoring and recording of system dynamics during reconnection it was thus necessary to arrange measurement at key points in the Croatian system (measuring points MP-1 to MP-6, see Fig. 2). Six measuring teams were established, all of them equipped with multichannel digital storage recording devices, to cover all major 400 kV substations (Tumbri, Žerjavinec, Ernestinovo, Melina and Konjsko) and HPP Dubrovnik as the farthest point in the southern part of the system (see Fig. 2). Measured quantities were bus voltages, frequency and active power flows in adjacent lines.

The measuring teams were equipped with recorders that had been at disposal at the time, which means that the devices were of various types and with different characteristics. However, the essential requirement that enough storage capacity must be available to enable continuous recording during at least 500 seconds with sample rate of at least 200 Hz per channel was satisfied in all cases. At HPP Dubrovnik the existing generating units' monitoring and recording system was used, which can record instantaneous values of relevant electrical quantities. Two recording devices were used at the 400/220/110 kV S/S Melina: a 4-channel digital storage oscilloscope as a primary recorder and another slow-sampling multichannel data acquisition system which was used to continuously record all signals at the substation during the course of reconnection. RMS values of relevant quantities at 400/110 kV S/S Ernestinovo, taken from measuring transducers, were also being recorded continuously from the beginning at 9:00 till 10:30 when the reconnection was completed. Ernestinovo was of special interest because both 1st and 2nd UCTE zone frequencies, representative for the global dynamics of the two zones, were recorded immediately before and after the synchronisation (i.e. switching on the 400 kV line Sandorfalva (H) – Arad (RO)). The frequency measurements were taken at the 400 kV bus (1st zone) and at the open end of the 400 kV line Mladost (SCG) – Ernestinovo (HR) which had been energized from the side of Mladost (2nd zone). The recorded signals at each measuring post were visually monitored on displays of the recording devices.

Snapshots of the Croatian power system steady states just before and after the moment of switching on of each individual 400 kV line were later extracted from the dispatcher analysis software package (DAM) at the National Dispatching Centre in Zagreb. The exact time values of switching the five 400 kV interconnection lines between the 1st and the 2nd zone were taken from sequence-of-events (SOE) recorder lists.

Because of short deadlines it was decided to use the existing built-in standard transducers for process measurements wherever possible. Only a couple of additional transducers were required at S/S Žerjavinec and Ernestinovo and those were temporarily installed just for the purpose of the measuring to be performed during reconnection.

Another problem was synchronisation and triggering of the recording equipment at the measuring posts, especially having in mind that different types of recorders were used. It was impossible in such a short time to arrange an automatic state-of-the-art synchronisation scheme (e.g., via GPS) nor it was possible to extensively check the synchronisation and triggering method well in advance of the D-day. Because of that the following simple solution was chosen: each team had been equipped with a precise radio-controlled clock, the clocks were adjusted in advance and checked immediately before the start of measuring, and then the internal clocks of the recording equipment at each measuring post were adjusted accordingly.

Since it was very important to minimize risk of triggering failures, it was decided to trigger the recording devices manually upon an order received by phone from the coordination centre (CP, see Fig. 2). Contact persons in the centre were in permanent phone contact with measuring teams and were giving them orders to start and stop recording according to instructions received from the main coordinator.

5. STEADY STATE OF CROATIAN SYSTEM BEFORE SYNCHRONISATION

Croatian 440 and 220 kV transmission system was in normal configuration with all lines in service except the 220 kV line Brinje – Mraclin. Total consumption was 1573 MW (about 55% of the peak load) and import was 473 MW. Power flow from Heviz (H) towards Žerjavinec (HR) was 696 MW. From stability point of view it is important that the 400 kV path from S/S Ernestinovo via BiH system to S/S Konjsko was in operation (see Fig. 2). Besides, all systems of the 1st and 2nd zones were in rather favourable steady state (Sunday morning).

6. POWER SYSTEM DYNAMICS DURING SYNCHRONISATION

The central event during reconnection was the synchronisation of the two zones. Immediately before the synchronisation there was a certain planned surplus generation in the 2nd zone because of which the 2nd zone frequency was slightly higher than that of the 1st zone (by nearly 40 mHz). According to available information, settings of the synchrocheck relay at S/S Arad were: Δf=50 mHz, ΔU=40 kV and $\Delta\delta$=10°.

Dynamic behaviour of selected quantities in Croatian system as recorded by "HR WAMS" during the synchronisation is shown in Fig. 2.

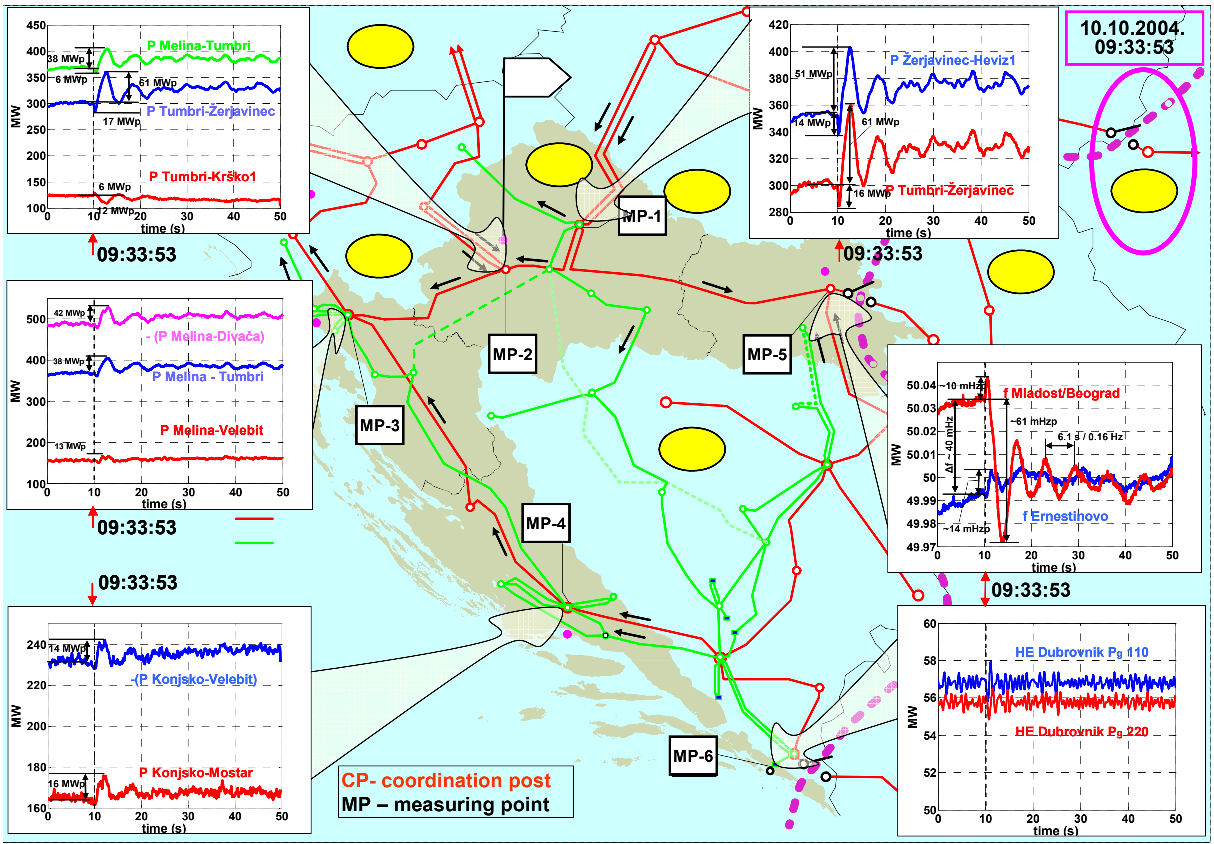

Figure 2 Dynamic behaviour of Croatian power system at synchronisation of the 1st and the 2nd UCTE synchronous zones as recorded by "HR-WAMS" (showing also the measuring points MP-1 to MP-6 and the coordination post CP and pre-synchronisation power flows)

It can be seen from the 1st and the 2nd zone frequency signals in Fig. 2 that at the very first moment the 2nd zone accelerates while the 1st zone decelerates. This may be explained by initial phase relations between bus voltage phasors at the synchronisation point. After that active power from the 2nd zone is dynamically injected into the 1st zone because of the initial surplus of generation and higher frequency of the 2nd zone. The electromechanical transient that follows is a damped oscillation with clearly identifiable low-frequency mode (0.16 Hz). Eventually, the two frequency signals coincide with each other as they are joined into one common UCTE frequency.

The disturbance caused by synchronisation then propagates from Hévíz to Žerjavinec and further through Croatian system towards S/S Melina as can be seen from active power oscillograms shown in Fig. 2.

7. INTERAREA OSCILLATIONS OBSERVED IN CROATIAN POWER SYSTEM

Interarea oscillations in Croatian power system were observed on previous occasions [2], [5] but they were mainly characterised by the 0.6-0.7 Hz mode that represented coherent motion of a group of hydro machines in the south (together with hydro machines in the southern part of BiH) – so called "southern" mode. Modes with lower frequency (in the range 0.2 to 0.3 Hz) which are known to be present in UCTE network [4] have been observed as well.

Three events during reconnection were the most informative as regards identification of interarea oscillation modes: P1 – synchronisation (switching on of the 400 kV line Sandorfalva – Arad), P3 –switching on of the 400 kV line Trebinje – Podgorica and P5 – switching on of the 400 kV line Ernestinovo – Mladost.

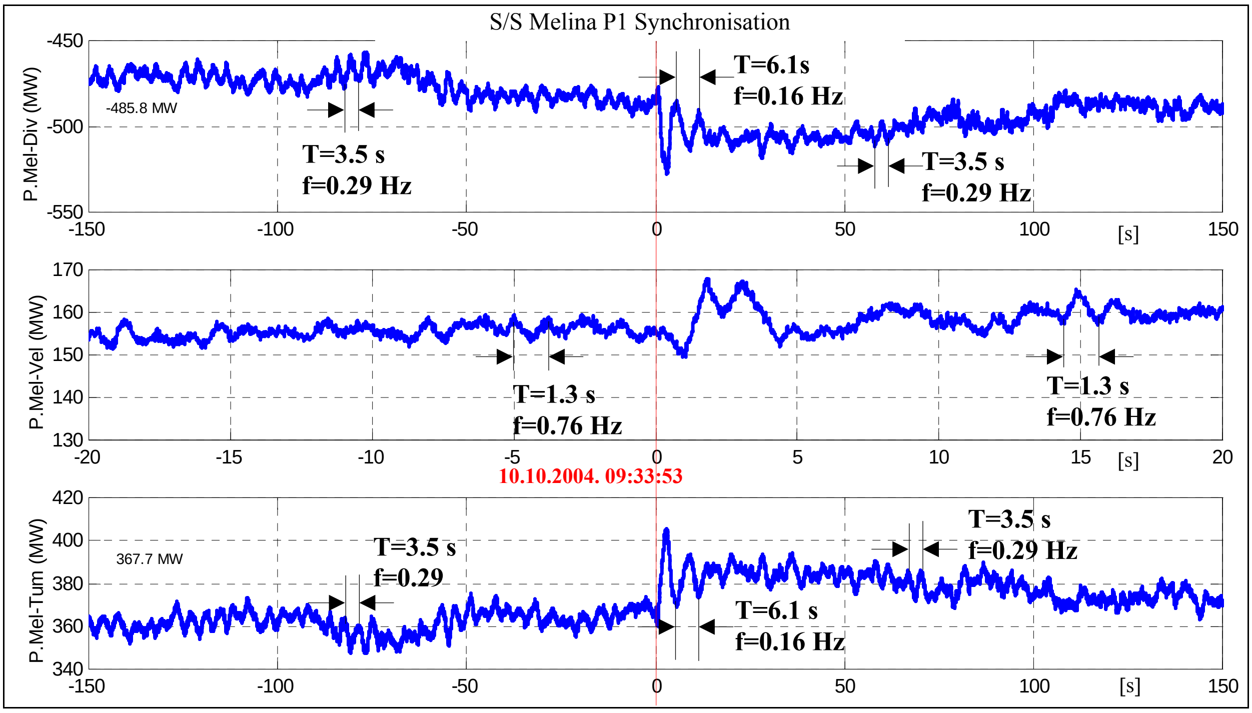

Figure 3 Interarea modes identified from active power flows in lines adjacent to S/S Melina before and after the synchronisation of the 1st and 2nd UCTE zones

The "southern" mode 0.76 Hz (period 1.3 s) can be seen in the active power flow in the 400 kV line Melina – Velebit (see Fig.2) recorded before and after the synchronisation (Fig. 3 in the middle – note that the time scale is different from that on the other two oscillograms to make the oscillations more easily visible!). The 0.29 Hz mode which existed before synchronisation remains present (Fig.3 top). The already mentioned 0.16 Hz mode observed in the 2nd zone frequency immediately after the synchronisation is visible also in power flows to and from S/S Melina (Fig.3, top and bottom).

By connection of the 400 kV line Trebinje – Podgorica the amplitude of the 2nd zone mode (see Fig.4) is increased in the south (lines Melina – Velebit and Melina – Divača) while it is decreased in the direction north-west (line Melina – Tumbri). These low frequency oscillations (2nd zone mode) have now become dominant in the active power in the 400 kV line Melina – Divača.

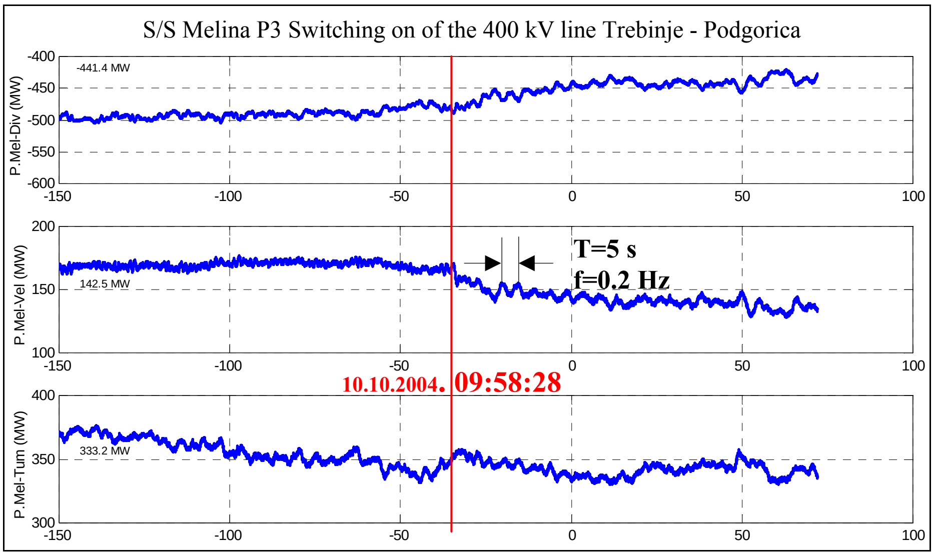

Figure 4 Active power flows in lines adjacent to S/S Melina at switching on of the 400 kV line Trebinje - Podgorica

Another example of poorly damped oscillations with frequency 0.24 Hz is given in Fig. 5. These oscillations are easily discernible in active power signal in the 400 kV line Melina – Divača before and after closing of the 400 kV tie line Ernestinovo – Mladost.

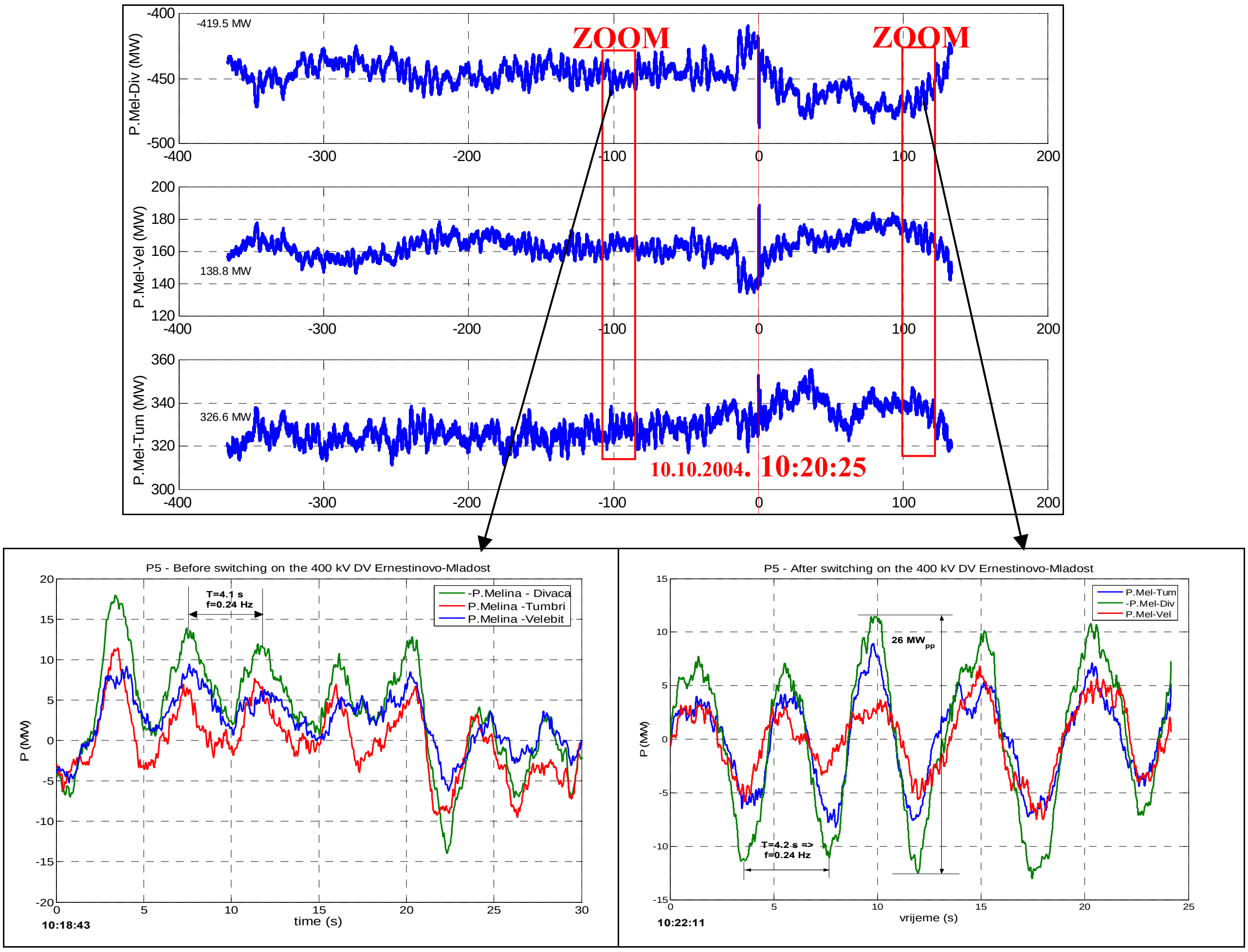

Figure 5 An example of poorly damped interarea mode observed in Croatian power system before and after connection of the 400 kV line Ernestinovo – Mladost

The interarea modes observed in signals recorded in Croatian system during reconnection of the 1st and 2nd zone may be roughly interpreted by equivalent “mass-spring” model as shown in Fig. 6.

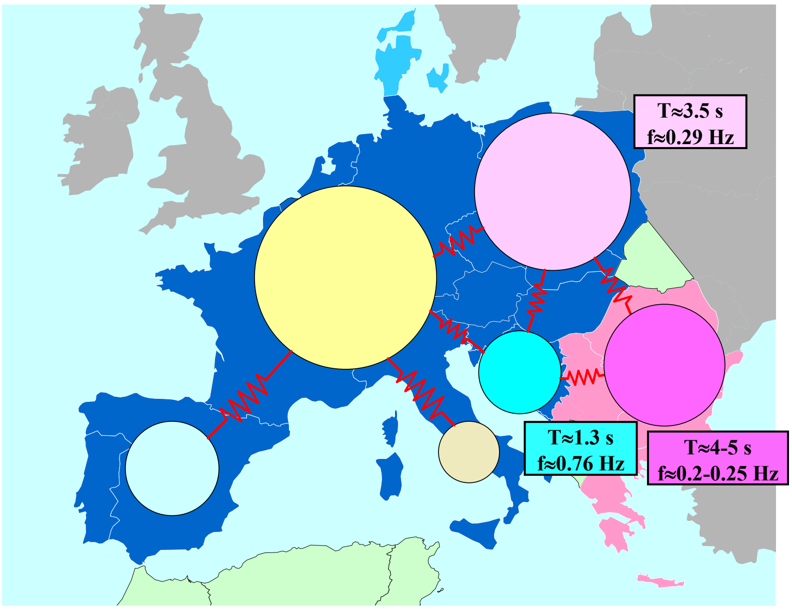

Figure 6 A simplified schematic representation of coherent groups in UCTE as identified from recording of Croatian system dynamics during reconnection of the 1st and the 2nd UCTE zone

8. DYNAMIC MODEL VALIDATION

The existing dynamic model of Croatian power system connected to UCTE that had been used till reconnection included dynamic models of neighbouring utilities (BiH, Slovenia, Hungary) and a suitable UCTE equivalent. After reconnection it had to be enlarged by incorporating the former 2nd zone. The 2nd zone model was built on basis of network topology and steady-state snapshots just before the resynchronisation and parameterised according to available information but relying heavily on assumed (typical) parameter values. The synchronisation of the two zones was seen as an opportunity to validate the model by comparison of simulation results with measurements.

Selected comparison results are shown in Fig. 7. In setting up the simulation scenario it was supposed that the voltage phase angle at Arad at the instant of synchronisation was 10° lagging behind the Sandorfalva voltage phasor (see Fig.8 at the right). The pre-synchronisation difference between the 1st and the 2nd zone frequencies was modelled by dropping an artificial load of 170 MW in the initially balanced 2nd zone and then letting power / frequency transients caused by dropping the load to settle down. It should be noticed that the measured frequency of the 1st zone immediately before synchronisation was about 10 mHz below the nominal value and was still changing with positive gradient. That effect was of course not modelled.

It can be seen from Fig. 7 that the former 2nd zone frequency signal is much better damped so that the oscillations die out in approximately 20 seconds. That signal also oscillates with higher frequency in simulation than in the real system. On the other hand, amplitude of active power swings in the 400 kV line Žerjavinec – Hévíz is considerably lower in simulation with somewhat lower frequency (see Fig. 7).

It may be concluded that the simulation essentially captures the nature of the observed electromechanical transients, but the differences between simulation and measurement indicate that a thorough revision of the simulation model may be necessary in order to obtain more realistic simulation results.

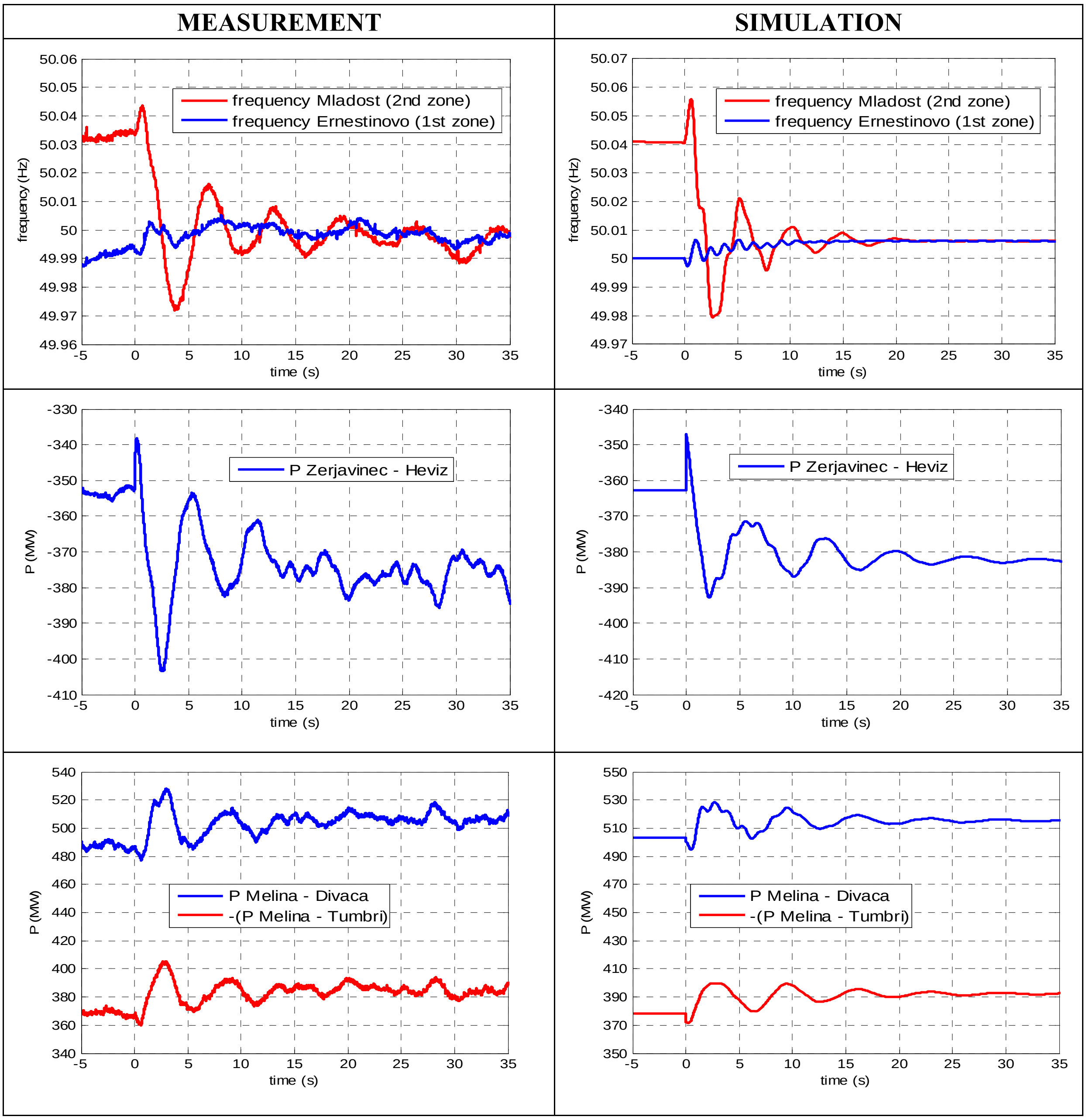

Figure 7 Synchronisation of the 1st and the 2nd UCTE synchronous zones – comparison of selected measurements and simulation results

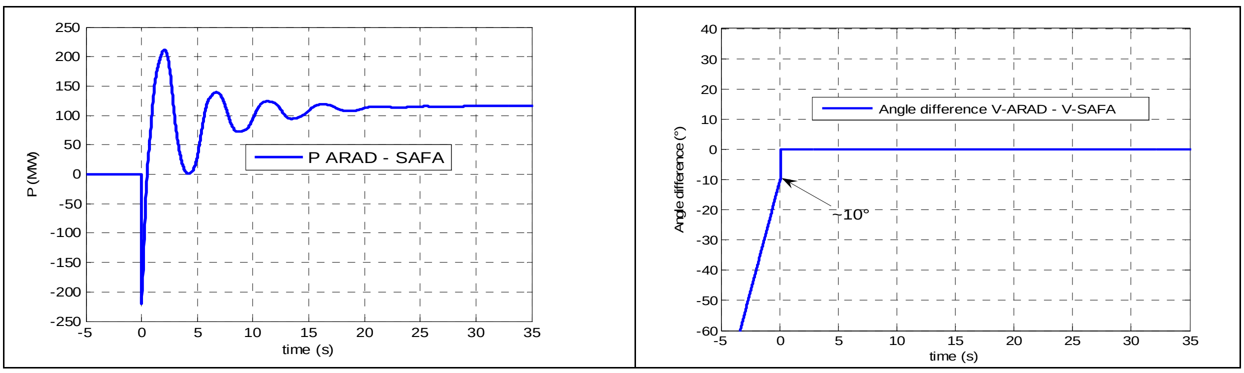

Figure 8 Synchronisation of the 1st and the 2nd UCTE synchronous zones – simulated active power flow in the 400 kV line Arad – Sandorfalva (left) and phase angle difference at the synchronisation point (right)

8. CONCLUSION

Use of WAMS for system-wide monitoring of power system dynamics is a current trend in power system operation. On some special occasions it is however desirable to extend monitoring to some parts of system that are not covered by WAMS. In such cases a dedicated wide-area measurement scheme should be arranged which would at least partially emulate WAMS functionality.

An example of the above approach was monitoring of Croatian system dynamics during reconnection of the two UCTE synchronous zones on 10 October 2004. In addition to UCTE WAMS monitoring, a wide-area measurement scheme was devised which enabled simultaneous and synchronised local measurements of active power flows, bus voltages and frequencies at several key points in Croatian system. Its main features were use of signals from existing transducers, phone communication between coordination centre and measuring teams, manual triggering, local storing of recorded signals and off-line collection and analysis of measurements.

From the gathered experience it is clear that the above mentioned measuring scheme has the following shortcomings in comparison with true WAMS:

- signals are recorded simultaneously but not transferred to a concentrating point and hence not available simultaneously and on-line at one place (e.g. NDC)
- measurements are not done continuously in a longer span (at least not at all measuring points) due to limited storage capacity of some digital recorders – this can be avoided by using more powerful recording devices
- time synchronisation of recorders can be done only approximately and additional effort is required in subsequent analysis – a more advanced synchronisation method would perhaps eliminate this problem
- it is rather complicated to organise and perform such a complex one-off measurement (several measuring teams must be at disposal, support personnel is required at the coordination centre, preparatory activities are needed at measuring posts, etc.)

However, the obtained results were very useful in assessing dynamic behaviour of Croatian power system, particularly after reconnection, and for validation of simulation models. Future work should include:

- further enhancement of Croatian WAMS (additional PMUs)
- better use of locally available recording devices and systems (e.g. measurement coordination and GPS synchronisation, specifying procedures for storing and collecting system event records, etc.) in order to supplement information available from WAMS, mainly for analysis of system events
- thorough revision of the power system dynamic model, especially regarding influence of the external system model to Croatian power system dynamics.

Finally, efficiency of PSSs in the former 2nd zone and their contribution to damping of the persistent and poorly damped interarea oscillations (2nd zone mode) should be examined.

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