Synchrophasor Applications in the Croatian Power System

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***Abstract*—Recent deregulation of electric industry markets within the Union for the Coordination of Transmission of Electricity (UCTE) in Europe is creating new opportunities for reliable, market-based transmission of electric power among participating countries. Croatia, which is strategically located in the southeastern part of the UCTE system, is seeing increased power flows across its territory, resulting in the need to improve existing data collection and monitoring systems. New challenges are being met through the use of synchrophasor-based technologies.**

This paper describes real-life experiences with the wide-area measurement system (WAM System) in Croatia. It describes power system topology, WAM system architecture, implementation details, visualization software, and the underlying communications system. The paper provides additional information about plans to integrate phasor measurement unit (PMU) measurements from neighboring transmission system operators and extend coverage from the existing 400 kV network to the 220 kV parts of the system and major generating resources. The paper concludes with analysis of recently recorded major system events.

I. Introduction

The Union for the Coordination of Transmission of Electricity (UCTE) was established in 1951. Its original role was to contribute to the development of economic activities through the exploitation of energy resources associated with the interconnection of electricity systems. In 1987, four new countries (Portugal, Spain, Greece, and the former Yugoslavia) joined synchronously with the eight original members. Connection lasted until 1991, when war destroyed key 400 kV substations and associated transmission lines within the former Yugoslavia, splitting the UCTE grid into two zones. Serbia, Montenegro, parts of Bosnia and Herzegovina, Macedonia, Greece, Albania, and subsequently Romania and Bulgaria formed the second synchronous UCTE zone, which operated independently for 13 years.

Successful reconnection of the first and second UCTE synchronous zones occurred on October 10, 2004. The European system was once again interconnected. This time, the system consisted of 24 member countries and created a synchronous zone covering almost all of Europe and extending to Africa (Maghreb countries), as Fig. 1 illustrates.

Croatia, which remained synchronized with Western Europe, played a key role in the reconnection process as Fig. 2 shows. Reconnection was made possible by the construction of the new 400/110 kV Ernestinovo substation, adjoining transmission lines, and the 400/220/110 kV Žerjavinec substation. The Croatian transmission system operator HEP-TSO performed the construction in coordination with the reconstruction of key transmission facilities in Bosnia and Herzegovina. New facilities reconnected parts of the former 400 kV "Nikola Tesla" ring, which the war has destroyed, resulting in reintegration and strengthening of the Croatian system and the systems of Bosnia and Herzegovina.

The role of the Croatian power system after the UCTE system reconnection became more important because its geographical position made it a natural link for energy transfer from northeastern to southwestern parts of Europe (see Fig. 1). On July 1, 2009, European transmission system operators joined together to form a common association called the European Network of Transmission System Operators of Electricity (ENTSO-E), which consists of 42 TSOs from 34 countries. ENTSO-E has fully integrated the work of six different TSO unions: UCTE, NORDEL, ATSOI, BALTSO, ETSO, and UKTSOA (www.entsoe.eu).

ENTSO-E is responsible for the bulk transmission of electricity on the main high-voltage networks. Because the continental European transmission system is connected into one large network managed by more than 30 different parties, it is complex and can be demanding for operation and control.

Another aggravating circumstance for the efficient control of power on such a large scale is the need to ensure efficient operation of the internal energy market. A novelty that developed with the introduction of the liberalized energy market is fast intraday change of power transfers on interconnection power lines between neighboring TSOs. This created a need for a new tool for real-time monitoring and control of power exchange on the high-voltage transmission network. Wide area synchrophasor measurement technology [1] filled this void.

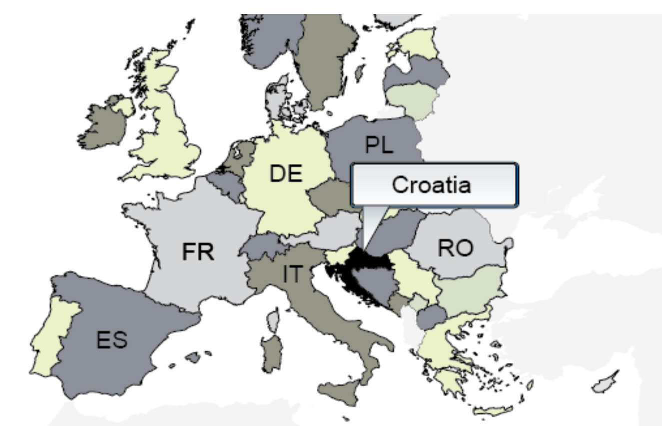


Fig. 1. ENTSO-E Association member countries

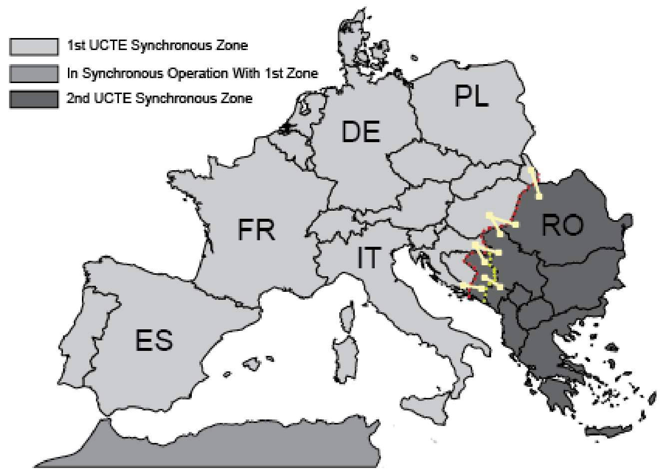


Fig. 2. UCTE Synchronous Zones 1 and 2 before the 2004 reconnection

The Croatian power system is one of the smallest in Europe. Because of its geographical position and the location of generating plants, the system for most of the year transports electricity from the south (where most of the hydropower plants are located) to the north (consumption center). Through reconnection of the UCTE synchronous Zones 1 and 2 (Fig. 2), the Croatian system has once again become a transit system. The average power transit through Croatia is about 30 percent of the total national load. The implementation of phasor measurement unit (PMU)-based monitoring enhanced the stability of the bulk power system and optimized the energy transit. Based on operational results collected to date, the PMU-based wide-area monitoring system is considered one of the principal tools for 21st century power system operation.

II. Initial Steps in WAM System Deployment

After thorough evaluation of the power transits that occur in the Croatian transmission network and the transits expected after the UCTE system reconnection, the Croatian transmission system operator HEP-TSO commissioned the first phasor measurement installation in 2003. This phasor measurement installation then monitored the heavily loaded corridor between Žerjavinec and Tumbri substations with online applications for stability assessment. Information about load flow and especially about average line temperature progression aided operational staff in fully utilizing transmission capacity and maintaining system integrity.

The devices were installed on the 400 kV transmission line, where they recorded voltage and current phasors, frequency, and rate-of-change of frequency. Satisfactory performance of the pilot project initiated the installation of three additional PMU devices in the remaining 400 kV substations, resulting in full observability of the 400 kV Croatian network. The decision about the location of the PMU devices was relatively straightforward; the devices would follow the shape of the power system. Because of the limited amount of data the system was transferring, it was possible to use a commercial grade computer as the phasor data concentrator.

HEP-TSO acquired the first dedicated phasor data concentrator (PDC) as a part of a turn-key system that included five PMUs from the same manufacturer. The PDC acquires synchrophasor data in IEEE C37.118 format and performs the processing. The PMUs acquire data at 50 measurements per second (every 20 ms) , while PDC records data at 10 measurements per second (every 100 ms). This was necessary because the PDC could not keep up with the amount of incoming data. Measurement errors are within 0.1º for phase angle. Apart from basic functions (recording, visualization, and archiving), the PDC processes data for advanced applications such as online system stability assessment (voltage stability, power oscillation monitoring, and phase angle monitoring). All results are available online in the National Dispatching Center control room.

III. Communications Infrastructure

A reliable communications system is a key requirement for a trustworthy WAM system. During the first pilot project, which used two PMUs, communications relied on a dial-up modem connection. This was satisfactory for the pilot project, but it could not be extended to a large number of PMUs; an improved telecommunications system was necessary. Subsequent deployment of an Ethernet (TCP/IP) connection used a private, all optical SDH network, with 2 Mbps communications channels reserved for each PMU. The most important requirement was that there be fast data transfer. The maximum time delay that the WAM system should tolerate (design target) was 20 ms, but test results showed much better performance: the longest transmission link delay was 1.8 ms. Further improvement of transmission reliability resulted from using a main and redundant channel. Subsequent extension of the SDH network, which included key parts of the 220 kV network, created a solid basis for future WAM system expansion.

IV. Data Interchange with Other TSOs

The former European association UCTE (now ENTSO-E) established a communications network that provides the necessary infrastructure to support data exchanges among TSO members. The Electronic Highway (EH) is a dedicated private network for real-time data exchange. TSO data receives the highest priority among all the other types of traffic, with EH availability exceeding 99.8 percent. Synchrophasor data exchange successfully exploited these two facts.

HEP-TSO presently exchanges real-time synchrophasor data with the Swiss TSO Swissgrid. The PDC stores voltage phasors and frequency measurement information from the Bassecourt substation PMU, in a 28-day circular database, serving as a virtual PMU. This enables HEP-TSO to monitor synchrophasor data from the central European part of the interconnected grid and make this information available online to system operators. Virtual PMU measurements (reduced PMU dataset) from Swissgrid proved to be of great value for the post-mortem analysis of the disturbances the power system recorded. Overall network topology is shown in Fig 3.

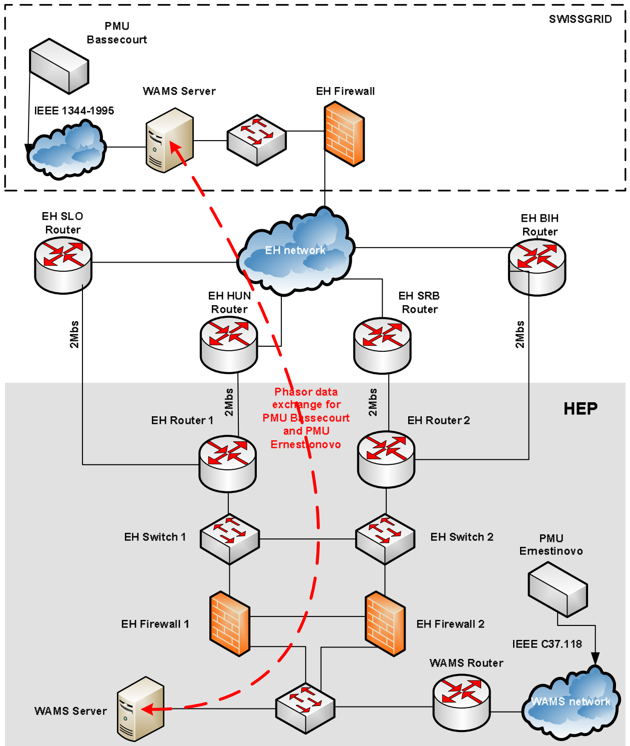


Fig. 3. WAM system communication network topology

V. Advanced Stability Assessment Applications

The main advantages of a WAM system compared to a classical SCADA system are its high data sampling rate and its GPS time synchronization. These features enable new applications that monitor online stability for a power system of interest.

The off-the-shelf wide-area monitoring system HEP-TSO acquired provided some of the main online stability assessment applications available at the time: voltage stability analysis of a transmission system corridor and power oscillation monitoring. The latter calculated power oscillation damping, magnitude, and frequency from the active power measurements signal or from the calculated phase angle difference signal between two substations. The application results revealed the behavior of the power system in stressed conditions and its interaction with neighboring power systems through the oscillation magnitude, damping, and frequency.

The monitoring function for operator support concerning voltage is built in a way that closely tracks the voltage profile / stability margins and that gives early warning of possible voltage collapse. An angular stability application, one of the most effective and simplest indicators of system stress, calculates the voltage phase angle difference between line terminals. It is also of great value during system reconnection maneuvers. The phase angle monitoring application also exposes the network stress resulting from heavily loaded lines. Additional applications that the original system could not implement include continuous, full data rate (50 samples per second) archiving, high-resolution modal analysis (more than three modes per feeder), and offline identification of oscillatory behavior (archived signal analysis).

VI. Recent WAM System Enhancements

Positive experiences with the WAM system in Croatia provided necessary justification for further increasing the number of installed PMUs and expanding the scope of data exchange with neighboring TSOs [2]. The main task was to eliminate drawbacks. In the first iteration, the mission was to improve the archiving system, visualization for the system operator, and system stability with online assessment applications [3]. The archiving in the original system was built as a circular database that stores 10 measurements per second with an archiving time of 28 days. The goal was to improve resolution to 50 measurements per second with a permanent database. The original system was primarily intended to meet the system operator's visualization requirements, but there was no possibility to add or remove chart or trend displays depending on user preferences. HEP-TSO identified this as the main issue for resolution in the next WAM system release. Data capture with 20 ms resolution also opened the possibility of improving system models and small signal stability assessment applications.

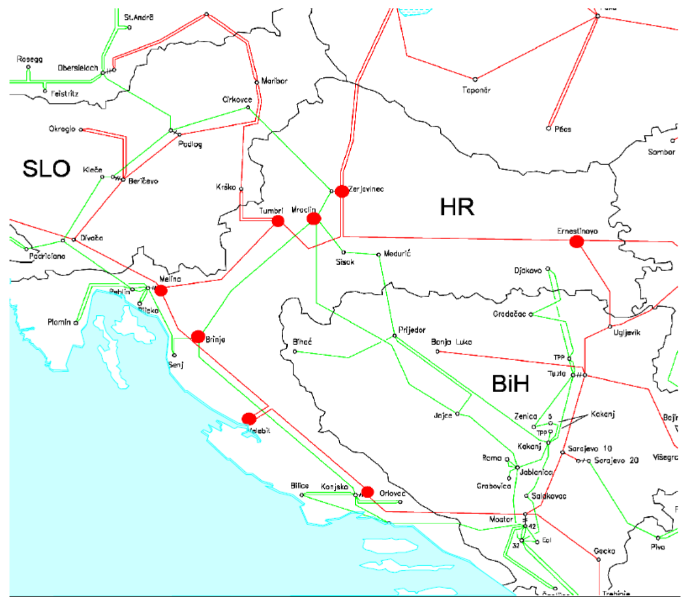


Fig. 4. Location of PMU devices in the Croatian Transmission System

The number of installed PMUs increased to 10 PMUs, which enabled HEP-TSO to monitor key parts of the 220 kV network. This provides full coverage of the main 400 kV and 220 kV south-north corridors for the purpose of improving overall system stability. Fig. 4 shows the current PMU locations (red dots).

VII. Introducing the Synchrophasor Vector Processor in the Existing System

In 2008, HEP-TSO acquired the Synchrophasor Vector Processor (SVP) and added it in parallel with the existing system. The main requirement for the new redundant PDC was to ensure no interference with (least service interruption) the existing system. The existing system has a production system classification, which means that it must be available 24 hours a day, seven days a week, and it is used by the system operator.

Great effort went into identifying appropriate system architecture. Requirements were that the system provide the following:

1. Ability to run multiple PDCs in parallel
2. Standards-based interoperability; ability to use devices from different manufacturers
3. Ability to process raw data gathered from more than 10 PMUs in the system
4. Application independence; the two PDCs do not affect each other in operation
5. Minimal changes to the existing configuration
6. No interruption of the production system operation
7. Scalability; ability to support future expansion

Connecting multiple PDCs to an existing PMU requires that the PMU simultaneously support multiple connections. With the PMUs already installed on the HEP-TSO system, the system met this requirement only partially. The PMU in question supports three simultaneous connections, but each of the connections is dedicated to a different communications protocol. These protocols include the now obsolete IEEE 1344 over TCP/IP, IEEE C37.118 TCP/IP, and the C37.118 UDP multicast. The existing production system uses the connection-oriented C37.118 TCP/IP protocol, leaving UDP multicast as the only feasible choice for the new system addition.

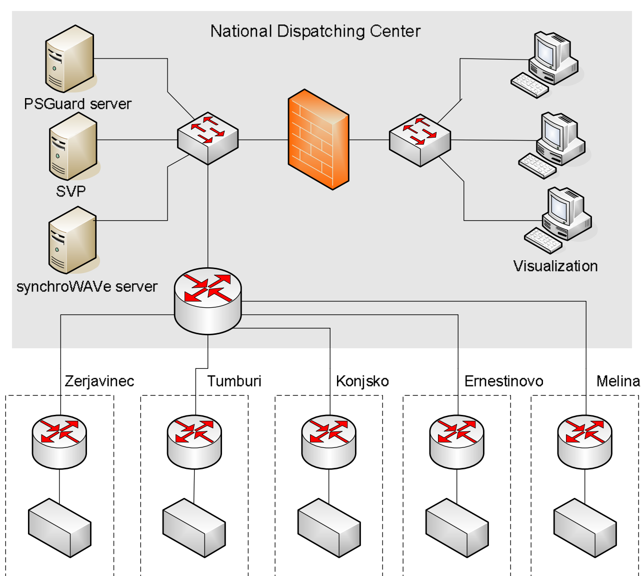


Fig. 5. WAM system architecture

Although initially an item of concern, the UDP solution proved an excellent match for this application. It satisfies all key HEP-TSO requirements, enabling 100 percent separation between the two PDC systems. Because the UDP implementation on this particular PMU supports both unicast and multicast type addressing, it can support a virtually unlimited number of parallel data collection systems.

With proper architecture design, it is possible to isolate and easily duplicate mission-critical applications such as visualization, archiving, and real-time wide-area remedial action scheme processing. One of the appealing possibilities being investigated includes the creation of an independent emergency control center with full visibility of all synchrophasor data flows.

The most significant change necessary in the existing deployment included the telecommunications router settings and the associated PMU settings. Modifications to the PMU communications settings enable the UDP/IP protocol stream (in addition to the already active TCP/IP protocol). In this way, the PMU device behaves as a multicast server that supplies data to several servers at the same time. This enables parallel distribution of raw synchrophasor data to the new PDC. The complete system architecture is shown in Fig. 5.

The PMU devices send data over TCP and UDP to the router, which redirects the information to the core SDH network. Three different servers acquire the incoming data streams:

1. PSGuard server acquires the TCP stream
2. Synchrophasor Vector Processor (SVP) acquires the UDP stream
3. Substation-hardened computer with SYNCHROWAVE® Server Software, archiving, and visualization acquires the SVP output

VIII. Post-Mortem Analysis with Wide-Area Monitoring Tools

As several years of WAM system operation in HEP-TSO have demonstrated, synchrophasor data information is a valuable source for detailed and thorough post-mortem analysis. The main benefit of the high-quality PMU recording is the precise time alignment of phasor data from different geographic locations. The PMU measurements enable the detection of disturbances and certain transient phenomena that were difficult to recognize previously. The analysis in the following text is based primarily on synchrophasor measurements and serves as an example of how certain disturbances can be identified according to frequency, voltage, and power measurement. Synchrophasor data are of strategic value for identifying disturbances located outside the borders of a TSO, as well as localizing a disturbance in the TSO and determining its severity. The results of the post-mortem analysis are exceptionally valuable for improving input data for algorithms in stability assessment applications.

One of the main events in UCTE interconnection history was the resynchronization of the 1st and 2nd synchronous zones in 2004. One of the preconditions necessary to fulfill before this resynchronization could occur was the harmonization of phase conductor sequences on all of the interfaces of the Croatian power system. HEP-TSO accomplished this successfully by rearranging the physical coupling on towers. Final act of rearrangement required careful balancing of local loads with generation and temporary islanding of the Croatian system from the UCTE grid. Because of close cooperation with neighboring systems

(ELES, MAVIR) and careful implementation of the detailed program, grid users were not affected. Island operation of the grids of Croatia and Bosnia and Herzegovina lasted only four seconds. The PMUs installed in the 400 kV Tumbri–Žerjavinec line captured this historic moment. Fig. 6 shows the frequency measurements acquired during this event. Point A is the separation point of the UCTE grid and Croatia, and Point B the point of regained synchronization.

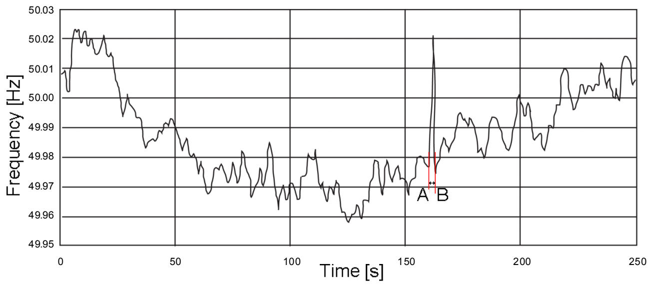


Fig. 6. Frequency recorded during islanded operation

Final resynchronization of the UCTE zones 1 and 2 occurred on October 10, 2004. Fig. 7 shows the coordinated sequence of events as seen through the voltage phase angle between the two zones (Switzerland to Greece)

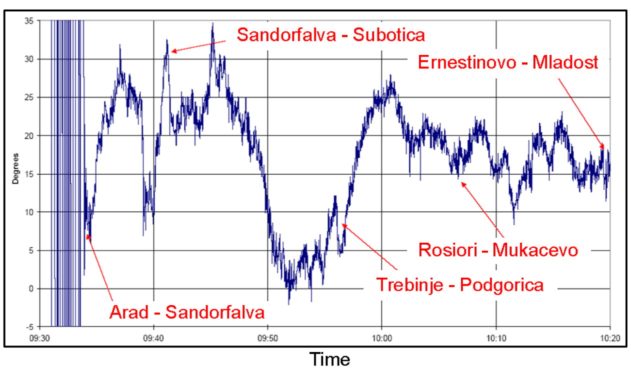


Fig. 7. Voltage phase angle difference during UCTE System resynchronization, Oct. 10, 2004. (Mettlen to Stefanos)

The valuable PMU measurements obtained during the islanded operation were used to establish initial trigger levels for the subsequent WAM expansion project. In this way, the system could register a disturbance such as the separation and resynchronization of the Greek power system with parts of Albania, Macedonia, and Kosovo that occurred in July 2007 and affected the Greek power system.

The WAM system easily detected this event Fig 8, which did not endanger the Croatian power system. From the first snapshots of the frequency measurement, it was immediately clear that the source of the disturbance was located near Croatia. The complete analysis of the active power and frequency signals showed that the disturbance occurred in the southeast part of the grid. Neighboring TSOs later confirmed this information, but the early warning provided by the WAM system was invaluable in properly classifying the event.

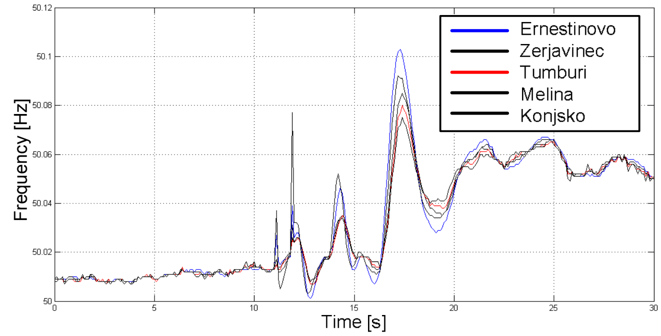


Fig. 8. System Frequency behavior during Greek power system separation

The active power flow changed towards Western Europe, which was an immediate indicator of power surplus in Eastern Europe. Fig. 9 shows the active power flow signal.

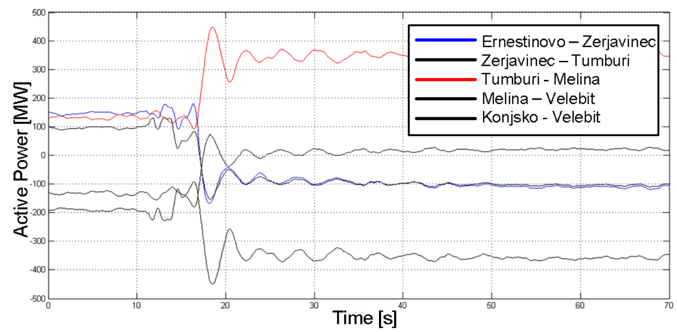
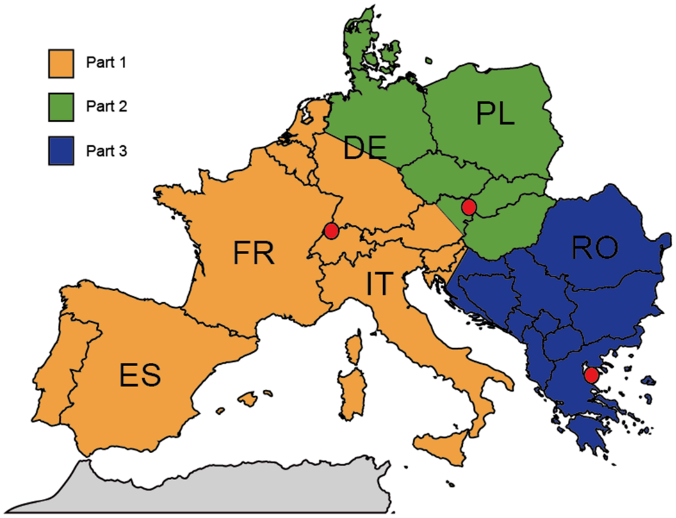


Fig. 9. Active power flow before and after the resynchronization

The incident occurred after cascading outages of several 400 kV lines in the Greek power system activated the defense plan that separated the Greek power system from the UCTE interconnection. The resynchronization process took place only 12 minutes later, and the system resumed normal operating conditions. The analysis of the disturbance served as a model case for proper setting of the application for power oscillation monitoring. The application registered two different oscillation modes, one between 0.6 and 0.7 Hz with a damping factor of 0.05, and the other with a frequency of 0.25 Hz and a damping factor of 0.1. These results were of special interest because this information had been unavailable before installation of the wide-area monitoring system.

The value of the WAM system was further recognized during the 2006 disturbance that affected the whole interconnected UCTE system. This disturbance, which originated in northern Germany, spread through the entire European grid. Cascade tripping of power lines caused the separation of the grid into three parts. Each part had its own frequency. Fig. 10 shows the splitting of the UCTE system, including the division of the Croatian power system into two parts.

The ability to monitor power system frequency at several points enabled early detection of system integrity loss, but the lack of data exchange with neighboring TSOs made it more difficult to understand the full size of the event.



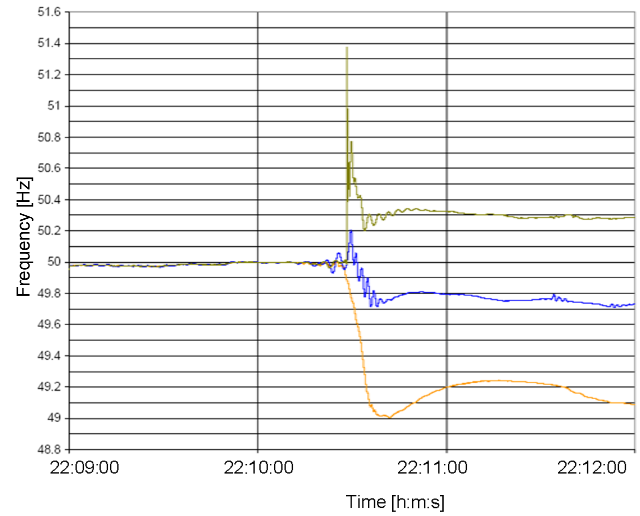


Fig. 10. Splitting of the UCTE system during the November 2006 disturbance (post event analysis)

During the disturbance in 2006, the frequency at the Žerjavinec substation dropped initially to 48.6 Hz, and recovery lasted longer than 10 minutes (Fig. 10).

Operating personnel tried to energize equipment tripped by the underfrequency relay, but switching was unsuccessful. Actual frequency recorded by the HEP-TSO at the very boundary of the breakup (Žerjavinec) is shown in Fig. 11. It exposes additional system dynamics which was invisible at the inner parts of the system (Swiss TSO recording in Fig. 10).

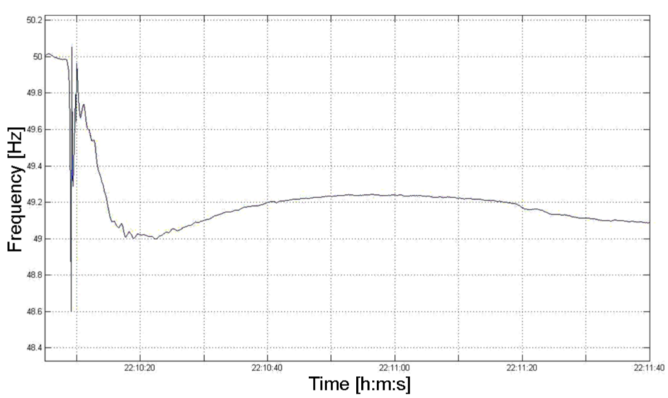


Fig. 11. Frequency drop observed during November 2006 event (Žerjavinec substation)

At the moment of the event, there was no information about the frequency at other system points. The only indicator pointing to system integrity loss was the change of phase angle between two substations (Fig. 12).

Once again; WAM system demonstrated its value in timely alerting the operator to a serious system condition, and providing the key information necessary to interpret the event. Future establishment of the Synchrophasor data exchange with neighboring TSOs will make the WAM system even more indispensable in everyday operations. It will make it possible to provide operators with real-time data display similar to that shown on the right hand side of Fig. 10.

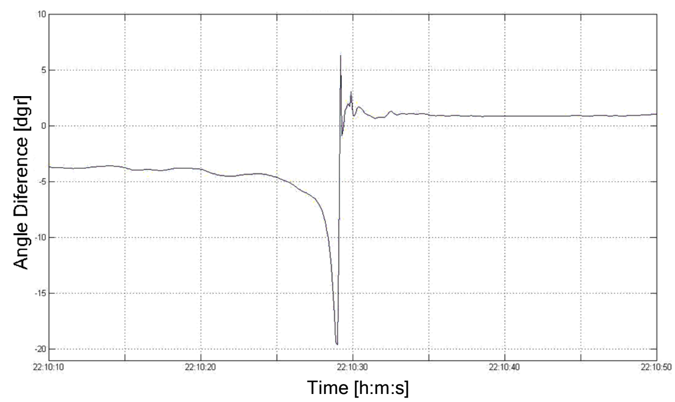


Fig. 12. Angle separation recorded during the November 2006 event (between Žerjavinec and Tumburi).

IX. Conclusion

This paper provides an overview of Synchrophasor and WAM system applications being deployed by the Croatian transmission system operator HEP-TSO. It places Croatian system in the wider aspect of ENTSO-E and documents operational advantages provided by the new technology. Paper gives details about WAM system history, ongoing and planned upgrades, communication infrastructure and overall system architecture. Paper concludes with a review of memorable events recorded by the WAM system during its 5 years of service, and documents the growing importance of this tool in day to day system operation. It vividly shows how wide area Synchrophasors can provide reliable, immediate feedback to the system operator.

X. References

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XI. Biographies

Zdeslav Čerina is Head of Development and Construction Coordination for the Division of Croatian Transmission System Operator - ICT Sector. He received his BSEE from Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia in 1985.

From 1986 to 1995, he worked for Koncar Electric Corporation, and from 1995-2000 he worked for EXOR company in several engineering positions concerning relay protection and substation automation (SA). He joined HEP - TSO in 2000, occupying several head positions in the company regarding relay protection and SA. In his current position, he is responsible for introducing new technologies for relay protection and SA. Zdeslav has written and co-written several technical papers in the area of relay protection.

His areas of interest include protective relaying applications and Wide Area Monitoring Systems (WAMS). He is chairman of Croatian National CIGRE committee B5 – Protection and Automation, and member of CIGRE B5 WG 06. He is a member of the UCTE Expert Group on Power System Stability and the National Board for Security and Reliability of Croatian Power System.

Ivan Šturlić was born in Croatia in 1978. He received the B.Sc. degree in electrical engineering from the Faculty of Electrical Engineering and Computing in Zagreb, Croatia in 2003. Since his graduation, he has been working in the ICT Department of HEP – TSO. He has developed numerous power system support applications using .NET technology. He is currently attending the Post Graduate Program at the Faculty of Electrical Engineering and Computing in Zagreb. His main topic of interest is development of distributed systems for collection, processing and distribution of phasor data measurements.

Renata Matica was born in Croatia in 1982. She received the B.Sc. degree in electrical engineering from the Faculty of Electrical Engineering and Computing in Zagreb in 2005. From 2005 to 2007 she worked in the area of relay protection with the HEP – TSO. Since 2007, she has been working in the ICT department of HEP – TSO. Currently, she is attending the Post Graduate Program at the Faculty of Electrical Engineering and Computing in Zagreb. Her main topics of interest are wide-area monitoring, protection and control, energy management systems. She is a member of the CIGRE B5 WG 14.

Veselin Skendžić is a principal research engineer at Schweitzer Engineering Laboratories, Inc. Mr. Skendžić earned his B.S. in Electrical Engineering from FESB, University of Split, Croatia; his M.Sc. from ETF, Zagreb, Croatia; and his Ph.D. from Texas A&M University, College Station, Texas. He has more than 25 years of experience in electronic circuit design, has lectured at FESB, and spent more than 20 years working on power system protection related problems. Veselin is a senior member of IEEE, has written multiple technical papers and patents, and is contributing to IEEE standards. He is an active member of IEEE PES, the IEEE Power System Relaying Committee (PSRC) and chairman of the PSRC Relay Communications Subcommittee.

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