RESERVE

D5.5 v1.0

Report on trial for frequency control in Laboratory and validation of initial network codes and ancillary service definitions, V2

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Abstract:

This deliverable provides a deep analysis of several major perturbations recorded in the Romanian power system by using the data recorded by Transelectrica with the help of the PMUs implemented to form a Wide Area Measurement System. The power system frequency was carefully analysed, and conclusions were drawn focussing on the importance of the mechanical inertia. Our analysis shows the need for developing Continental Wide Area Measurement System (WAMS), eventually incorporating real-time stability analysis. This is because the specialists are still not able to understand the behaviour of the Interconnected Network of the Continental Europe.

Keyword list:

Frequency, synchronised measurements, phasor measurement units, reporting rate, wide are measurement system, transient stability analysis.

Executive Summary

This deliverable is the second version of the report on frequency analysis based on real data measurements and contains qualitative and quantitative information necessary for understanding the dynamic behaviour of a power system, in particular the Romanian power system, under various perturbations. We aim to understand:

- The importance of mechanical inertial during transient periods;
- The spread of a perturbation over a wider area in case of rapid frequency variations;
- The differences between frequencies, during slow variations, in different countries of the Interconnected Network of the Continental Europe.

In this deliverable (D5.5) we have presented the records of frequency during several perturbations experienced by the Romanian power system. These perturbations are presented in the annexes and are briefly described as follows:

Event 1: Sudden disconnection of one 700 MW nuclear unit. Two events, but with different conditions have been experienced in 2017 and 2018.

Event 2: Loss of about 1000 MW in coal-fired power plants following three consecutive short-circuits caused by meteorological conditions.

Event 3: A continental event (no official final report issued by ENTSO-E) that caused the frequency to drop by 200 mHz.

Note that other events have been recorded, but their impact on the system frequency is small, so that they present no relevance for frequency stability. None of the recorded events was desired nor expected, but their occurrence helps us to understand the strength of the Romanian power system under the actual operating conditions, with large mechanical inertia available in classical power plants.

All the data have been recorded by Transelectrica by means of the PMUs installed in the most important 15 buses of the Romanian power system, some of them found at the border with the neighbouring power systems, while others are located on the premises of the largest power plants, including wind power plants. The data have been collected with a reporting rate of 25, which means that data are reported every 40 milliseconds, all data being synchronized by means of the European satellites.

The main conclusions resulting from our analyses are:

- The largest mechanical inertia in the Romanian power system is available in the two nuclear units, which are located in the Dobrogea area. In some operating conditions it accounts for about 40% of the total mechanical inertia in the Romanian power system. The disconnection of one unit will create a significant frequency dip, whereas the disconnection of both units can lead to variations that require careful analysis. This is because the Dobrogea area accommodates the largest part of the wind power plants in Romania, and in the case that CNPP will be dismantled until 2050, while the power installed in wind generation is significantly increased in Dobrogea, the lack of mechanical inertia could cause frequency instability by local or inter-area oscillations.
- In the case of a short-circuit, followed by losing a large amount of power generation, inter-area oscillations are observed. This observation is very important to anticipate the behaviour of the Romanian power system in the future, when the share of renewable energy sources is increasing towards 100%.
- During slow dynamics, the synchronous machines from the Interconnected Network of the Continental Europe are swinging together. This is seen by the synchronized values of the frequency recorded in different countries.

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1. Introduction

1.1 Aim of Task 5.3

The *Renewables in a Stable Electric Grid* (RESERVE) project aims at researching new energy system concepts, implemented as new ancillary services enabling distributed, multi-level control of the energy system using pan-European unified network connection codes. In particular, Task 5.3 focuses on analysing frequency data and performing frequency control simulations on the Romanian power system database aiming at identifying particular dynamics of the frequency in scenarios with power generation from RES up to 100%. Two deliverables are produced within this task as follows:

- **Deliverable D5.4** focused on the measurements within the UPB laboratory set-up. Theoretical considerations have been presented together with measurement data from different points in the Romanian power system. The highlights of this study are: the analysis of measurement latency for PMUs, the comparison between frequency measured in a synchronized manner in several locations, at different voltage levels, and the impact of time data aggregation as described in IEC61000-4-30. For the different cases studied here, raw data, aggregated data and/or statistical information have been presented. The analysis of the frequency data performed within Task 5.3 was intended to identify, by using high sampling rate measurements, the frequency dynamics that may occur in the power system. In deliverables D2.1 and D2.2 it was shown that these dynamics are more difficult to handle with the actual technology, because frequency experiences faster and deeper variations.
- **Deliverable D5.5** extends the analysis on the use of high reporting rate synchronized measurements collected by means of the WAMS implemented in the Romanian power system, as enabler of RES participation in the frequency control operation. Power flow data and frequency data are required to achieve complete and correct analysis on the power system dynamics in terms of frequency control in the case of small or large perturbations, e.g. unexpected sudden unbalances caused by disconnection of generation units following severe short-circuits or wide area frequency variations caused by simultaneous multiple incidents. Frequency variations are presented for several significant power system incidents, recorded both in the Romanian power system and in in Interconnected Network of the Continental Europe, then relevant conclusions are drawn in terms of system robustness and transient behaviour.

1.2 Objectives of the Work Report in this Deliverable

The work report in this deliverable aims at:

- Presenting the general aspects regarding the continuation of the measurement campaign in the Romanian power system using the WAMS owned by Transelectrica. The PMUs installed at various buses cover the whole power system as they are located at the border buses, as well as at the 400 kV buses that accommodate the largest power plants in Romania;
- Analysing the most relevant incidents that occurred in the Romanian power system consisting of large power unbalances, as well as continental incidents that affected the frequency in Romania; these analyses are intended to estimate the robustness of the Interconnected Network of the Continental Europe to the most severe perturbations.
- Providing conclusions on the use of high reporting rate synchronized measurements on wide area as enabler of RES participation in the frequency control operations; these conclusions are drawn based on the statistical analysis provided in deliverable D5.4 and on the analysis provided in the annexes of this deliverable regarding the impact on the power system stability of the various major incidents for which frequency records have been obtained;
- Providing recommendations for the power systems of the future characterized by an increased share of renewable energy sources, up to 100%.

1.3 Outline of the Deliverable

The deliverable details the research efforts in the second half of the project on identifying and analysing major grid perturbations using high reporting rate

synchronized measurements provided by the WAMS owned by Transelectrica. Data have been collected during four major incidents that resulted in abnormal frequency variations in the Romanian power system. The research activities have been conducted to emphasize frequency particularities, that otherwise cannot be observed, e.g. the influence of the reporting rate on the quality of the frequency in transient conditions, the importance of the measurement point (influence of the network impedances) in the power system.

1.4 How to read this document

The present deliverable covers the realization of frequency measurement and data analysis within the research activity focusing on the importance of high reporting rate on the quality of frequency data for stability analysis at wide level of the Romanian power system by using fifteen compatible PMUs installed at the most important buses. This document can be read in correlation with deliverable D5.4 as it is a continuation of the measurement and event analysis started at the beginning of the project. While the first phase of the measurement campaign, with the results presented in deliverable D5.4, aimed at analysing the measurement data from quality and statistical point of view, the second phase of the measurement campaign focused on analysing the stability aspects at the power system level.

Figure 1.1 shows the placement of this deliverable (**D5.5**) in the wider context of **Task 5.3**, within the work package **WP5**, as well as the interlinked work packages of the RESERVE project.

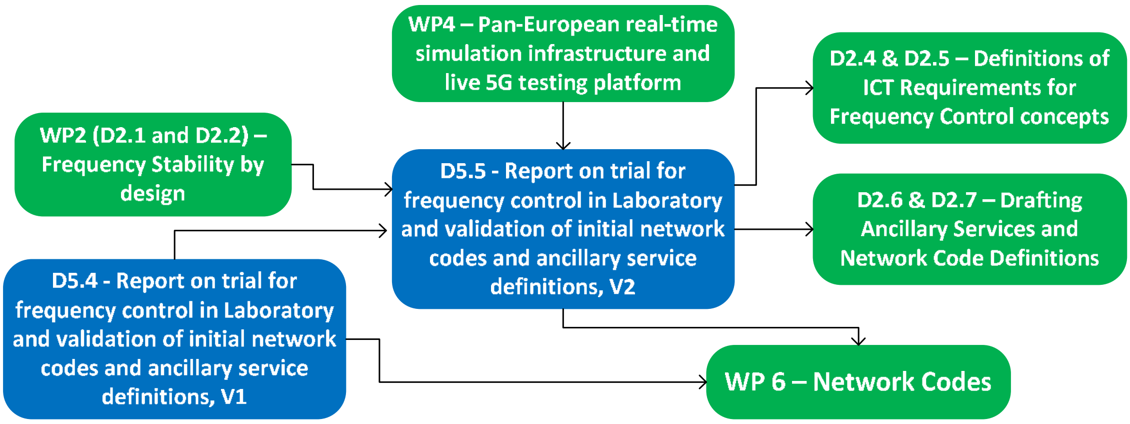

Figure 1.1. Relationships between Deliverables in Task 5.3 and other work packages.

The observations resulted in this deliverable, together with those from deliverable D5.4 have been used as inputs for drafting network codes proposals in Work Package 6. Technical aspects related to frequency control provided in deliverables D2.1 and D2.2 are guidance for collecting the relevant data within the activity of Task 5.3 and complete the analysis. The conclusions resulted from the first phase of the campaign of frequency measurements are integrated within this document to provide a complete framework related to the importance of high reporting rate measurements with the help of PMUs. The conclusions presented in this deliverable (D5.5) are in accordance with the results of simulations carried out within WP2 for drafting ancillary services and network codes related to power system frequency control.

2. The need for developing WAMCS

2.1 The context

The use of Wide Area Monitoring System (WAMS) has been extensively discussed in literature [1][2], while various projects have been implemented by system operators. A WAMS is designed for monitoring purposes only. The real-time data recorded [3] by PMUs are only displayed by WAMS, usually as a post-event activity.

The most severe perturbations, called *large disturbances*, are:

- Short-circuits occurring near heavy loaded generation units;
- Disconnection of large generation units;
- Disconnection of large loads;
- Disconnection of interconnection lines as a result of a short-circuit.

These perturbations cause large oscillations of the rotor speed of the synchronous generators. Theoretical and practical studies have shown that if the magnitude of these oscillations exceed a certain threshold, called the *stability limit* [4], the generator becomes unstable, the control systems are not capable of synchronizing the generator in appropriate time, and protection and automation system trigger the disconnection of the generator.

Various solutions have been developed to improve the stability limit of the synchronous generators. However, these are effective only by using local measurements of the frequency or other quantities. The dynamic operation of the Interconnected Network of Continental Europe takes new dimensions, and the challenges are coming from:

- *The uncoordinated unit commitment across Europe*. All electricity markets in Europe use one-hour as the dispatching interval. This means that, no matter of the time zone, all generation sources shift from the power set-point to the other as the same time. This causes often visible frequency drops. During this time, the hazard of simultaneous incidents can lead the power system into a condition that lead to inter-area power oscillations and angle or frequency instability.
- *Uncoordinated control of the RES's inverters*. The inverter-based power plants are not provided with synchronization-torque capability. This means that they are passive systems and do not contribute to the synchronization of the generation units after perturbations, and therefore amplified power oscillations may be experienced. The linear swing dynamics (LSD) theory developed within RESERVE (presented in deliverable D2.3) is intended to provide a solution in this context that makes the RES-based generation units contribute to the system stability.

Because of the fast phenomena, the transient stability must be evaluated on-line. This is possible by extending WAMS to WAMCS (Wide Area Monitoring and Control System). Based on the on-line monitoring and stability assessment, immediate control actions related to frequency and transient stability can be taken to limit the spread of the effects of a perturbation.

2.2 Developing a WAMCS at Transelectrica

The frequency control laboratory trial is located in Romania and is based on data from the power grid of the TSO Transelectrica. A set of Phasor Measurement Units (PMU) is installed in the Romanian power system. As also presented in deliverable D5.4, and in Annex A, the WAMS at Transelectrica consists of 15 PMUs located at the border buses of the Romanian power system and at the 400 kV buses that accommodate the largest power plants (Figure 2.1).

All the data provided by the 15 PMUs are sent to Power Data Concentrator (PDC) located at the National Dispatching Centre (NDC).

The WAMS does not operate in real-time and thus no graph is displayed in real-time. The records of any event of interest are displayed in off-line analysis, after selecting manually the time window of interest. This application was a first step in developing a WAMCS. Three applications can be implemented in real-time, i.e. Transient Stability monitoring, Frequency Stability monitoring, and dynamic State Estimation. Starting from this, Control capabilities will be implemented.

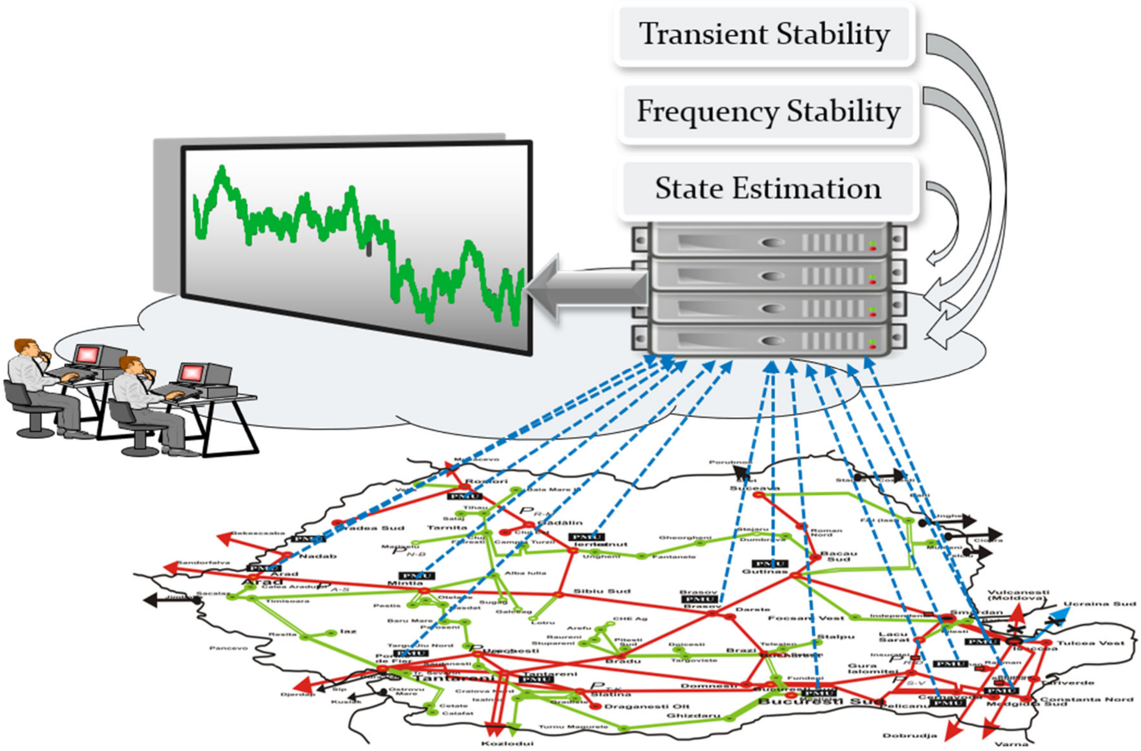

Figure 2.1 Placement of PMUs in the Romanian Power System.

Transelectrica, the Romanian TSO, has provided datasets for use in RESERVE activities which were recorded during severe perturbations with significant impact on the system frequency. These datasets are used as input scenarios for off-line simulations to test and validate frequency control strategies on various time scales and to propose new and modified network codes and ancillary services [5].

Monitoring system frequency, using the data measurements provided by PMUs, helped RESERVE to understand the dynamic behaviour of the Interconnected Network of Continental Europe. One of the most important questions within the RESERVE project is to determine whether the frequency differs significantly at remote points in the ENTSO-E power system. This issue is analysed in both very short time-frames (1-2 seconds, specific to short-circuits, but with limited geographical impact) and in a quasi-steady-state time-frame (>5 seconds, specific to power unbalance, when the same effects could be experienced by the entire interconnected power system).

2.3 Event analysis

Several events were analysed based on the datasets provided by Transelectrica. These events are grouped into categories and presented in detail in annexes B and C, together with relevant conclusions related to frequency stability. These events are:

Event 1.1: Sudden disconnection of one 700 MW nuclear unit, out of the two units at Cernavoda Power Plant on June 1st, 2017, at 00:35 CET. Note: the other unit was off-line at the instant of the event. (See Annex B2.1).

Event 1.2: Sudden disconnection of one 700 MW nuclear unit, out of the two units at Cernavoda Power Plant on August 16th, 2018, at 16:56 CET. Note: the other unit was in operation the instant of the event. (See Annex B2.1).

Event 2: Loss of about 1000 MW in coal-fired power plants following three consecutive short-circuits caused by meteorological conditions. (See Annex B2.2).

Event 3: A continental event (no official final report issued by ENTSO-E) that caused the frequency to drop by 200 mHz. (See Annex C).

Note that other events have been recorded, but their impact on the system frequency is small so that thy present no relevance for frequency stability. None of the recorded event was desired nor expected, but their occurrence helps us to understand the strength of the Romanian power system under the actual operating conditions, with large mechanical inertia available in classical power plants.

The conclusions drawn from the analysis of these events are also presented in the Conclusions chapter.

As explained earlier, Transelectrica's WAMS includes a software application installed on a server at the National Dispatching Centre that can visualize the several types of data. As an example, the records of *Event 2* are displayed in Figure 2.2. Chart (1,1) shows the frequency, Chart (1,2) shows the active power, Chart (2,1) shows the voltage magnitude, and Chart (2,2) shows the voltage angle.

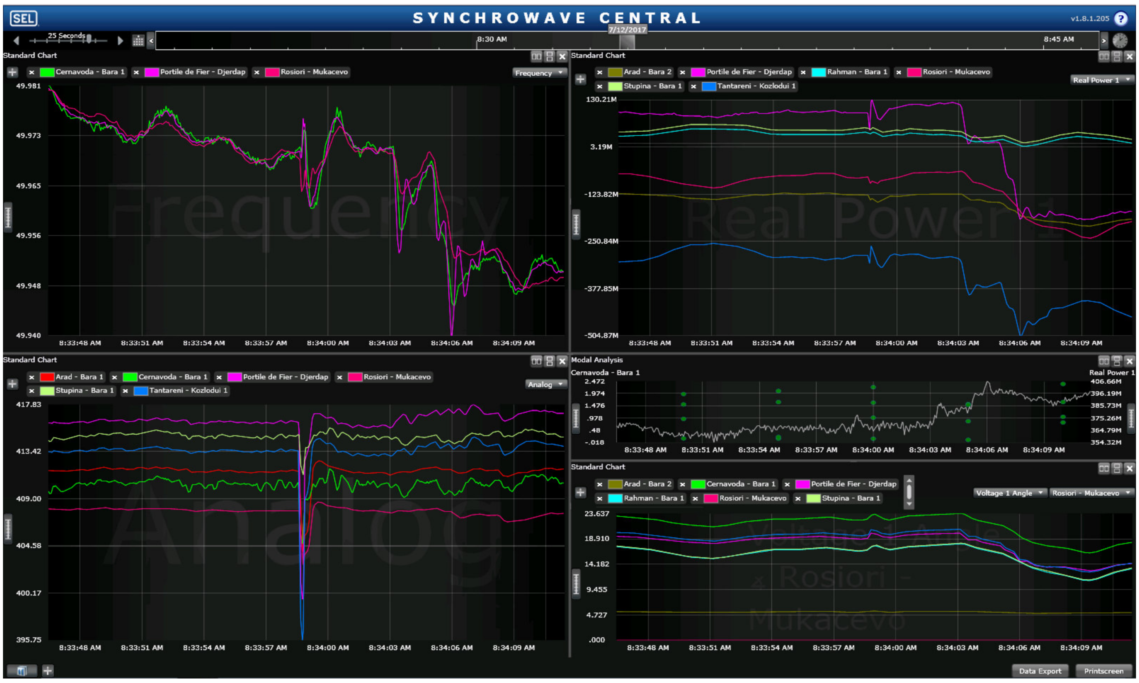

Figure 2.2 Snapshot of the Transelectric's Synchrowave application analysing the series of events presented in Annex B.2.

Figure 2.3 Zoom on the Chart (1,1) shown in Figures 2.1

In terms of frequency, the impact of each short-circuit on the frequency stability can be clearly observed in Figure 2.2. The oscillations damping was possible due to the large mechanical inertia power plants located in the proximity of the incident.

2.4 Recommendations for network codes and ancillary services

Based on the work done during the whole period of the project within Task 5.3, the following proposals for network codes have been updated:

- **New definition of the concept of frequency** is necessary in fully agreement to the model adopted for the control purposes. In transient conditions the frequencies at different busses are different. However, the measurements are performed by PMUs, which are equipment adopting the phasor model, i.e. referencing the phase difference to a unique frequency signal. The contradiction should be solved by appropriate choice of both measurement and control models, and applied into a similar numerically simulated context.
- Recommendation regarding the **minimum reporting rate** and the **minimum calculation interval for rate of change of frequency (RoCoF) [6]**, under the same condition of adopting a non-ambiguous definition of frequency and rate for change of frequency quantities should be provided at the ENTSO-E level.
- **Developing a WAMCS at the Continental level** is a prerequisite. Standardized data exchange procedures should be developed by ENTSO-E in order to collect appropriate frequency and phasor data to allow identifying the origin of the critical events. Based on this, and using the local measurements, frequency control actions are to be taken in accordance with the recommendations developed within the RESERVE project.
- Procedures for time-aligning (and resampling) of **synchronized information from measurement units characterized by different sampling rates** should be developed. This is also necessary when measurement information from low cost PMUs are used in off-line analysis.

3. Conclusions

Analysing the frequency data collected with the PMUs owned by both Transelectrica and UPB, the following conclusions can be drawn related to the dynamic behaviour of the Romanian power system:

- The largest mechanical inertia in the Romanian power system is available in nuclear units. In some operating conditions it accounts for about 40% of the total mechanical inertia in the Romanian power system. The disconnection of one unit will create a significant frequency dip, whereas the disconnection of both units can lead to variations that require careful analysis. Since the Dobrogea region is located at the border of the ENTSO-E system, in the near future, when the fossil fuel power plants will be dismantled, we expect that the sudden disconnection of one nuclear unit, or a large WPP, can cause frequency instability by local oscillations.
- The loss of important mechanical inertia leads to large frequency excursions. The most important variations occur in the first 200-500 milliseconds. This time interval is important in the attempt to make proposals related to the calculation of RoCoF or RoCoP that are applied to very fast controls.
- The loss of a large nuclear unit can be classified as large perturbation. However, due to the strong interconnection of the Interconnected Network of the Continental Europe, the frequency was recovered very fast after both events (Annex B.1), first by the intervention of the inertial response, then following the contribution of the frequency containment control.
- In the case of a short-circuit, followed by losing a large amount of power generation, inter-area oscillations are observed. However, the generators are quickly synchronized, within 2 seconds, thus starting to swing together, due to the strong interconnection of the Romanian power system and to the mechanical inertia inherited in generation units located near the location of the faults. This observation is very important to anticipate the behaviour of the Romanian power system in the future, when the share of renewable energy sources is increasing towards 100%.
- During slow dynamics, the synchronous machines from the Interconnected Network of Continental Europe swing together. This is seen by the synchronized values of the frequency recorded in different countries.
- Low-cost PMUs can provide data with acceptable accuracy [7]. For better results, a dedicated software that synchronizes the data in strings of data with different reporting rate or with missing data is needed.
- Developing a Wide Area Monitoring System across Europe is essential for capturing both fast and slow dynamics to help us analyse and understand the behaviour of the various system dynamics, while pattern recognition may help better identify the origin of the incident. The incidents produce firstly local frequency variations, while all the other areas remain unaffected, then the frequency quickly becomes similar in every point.
- Measuring the frequency in the Romanian power system is very important for the analysis because Romania is located at the border of the Interconnected Network of the Continental Europe, and it is expected that the frequency can have a different behaviour on a short term as compared to a bus located in the centre of Europe.
- The frequency at the 400 kV bus in Cernavoda exhibits high-variation oscillations, which are visible after each event. The same occurs at the other end of the Romanian power system at the Rosiori bus, but with lower magnitude. The oscillations reveal the attempt of the control systems attached to the generation units accommodated at the two buses to maintain the synchronism and stability.
- The most severe perturbation in a power system is the short-circuit. Although the same operating conditions cannot be recreated in a simulation because of the very large amount of information, simulation of similar conditions is worth considering, in order to compare the results that can be achieved by simulations with those from a real system. The actual power system is characterized by large mechanical inertia and fewer renewable energy sources. This is why the simulation of future characteristics of the power system will reveal different results than those obtained from real measurements.
- The use of synchronized measurements by means of PMUs is very important for developing wide area monitoring systems because they help to capture very fast dynamics, which is useful to analyse and understand the behaviour of the

interconnected power system in real conditions. Direct conclusions by experts help in making decisions without performing off-line simulations.

- The analysis performed in the second part of the project and presented in this deliverable was possible because of the data provided by Transelectrica, which have been achieved by means of the fifteen PMUs, with a reporting interval of 20 milliseconds. Such granularity of data allows capturing the fast dynamics of the frequency. In this context, development of a WAMCS helps the power system operator to take appropriate decision in order to maintain its stability.

All these observations have been used in drafting the final proposals for network codes or standards.

4. References

[1] Peter Wall, Papiya Dattaray, Zhaoyang Jin, James Yu, “Deployment and demonstration of wide area monitoring system in power system of Great Britain”, presented in Journal of Modern Power Systems and Clean Energy, Springer, Volume 4, July 2016.

[2] L. Ramesh, S. P. Chowdhury and S. Chowdhury, "Wide area monitoring protection and control - A comprehensive application review," 10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change, Manchester, 2010, pp. 1-4.

[3] Mihaela Albu, Alexandru Nechifor, „Extending OpenPDC into a versatile Data Concentrator for synchronized measurements”, presentation at Wide View - The use of telecommunications and GPS technology for the real-time wide-area monitoring and control of power systems Seminar, 11-16 March 2013, Nicosia, Cyprus.

[4] S. Savulescu (ed.) et al, “Real-Time Stability in Power Systems”, Springer, 2014.

[5] ENTSO-E Network Code / Commission regulation on establishing a guideline on electricity transmission system operation, voted in comitology on 4 May 2016.

[6] Albu, M., Dumitrescu, A.-M. Popovici, “Rate of Change of Frequency - a Power Quality Descriptor”, 2014 IEEE 16th International Conference on Harmonics and Quality of Power (ICHQP), 2014.

[7] P. Romano, M. Paolone, T. Chau, B. Jeppesen and E. Ahmed, "A high-performance, low-cost PMU prototype for distribution networks based on FPGA," *2017 IEEE Manchester PowerTech*, Manchester, 2017, pp. 1-6.

[8] Florin Balasiu, Felicia Lazar “Improve Power System Operation Through Synchrofazor Applications”, WEC Regional Energy Forum FOREN 2010, Romania.

[9] Daniel Dumitrascu, Ionut Barburas “Aplicatii utilizand echipamente PMU in SEN”, WG-B5 CNR CIGRE, Vidraru 2015, Romania.

[10] Transelectrica, The single-line diagram of the Romanian power system. Online: http://www.transelectrica.ro/widget/web/tel/sen-harta/-/harta_WAR_SENOperareHartaportlet

[11] Timetools Limited. (2015, Jul.) LC2750 GPS Time Server Data Sheet. [Online]. http://www.timetools.co.uk/solutions/gps-time-server/

[12] https://cdn.selinc.com/assets/Literature/Product%20Literature/Flyers/5078-2_PF00282.pdf?v=20170615-090842

[13] IEEE, C37.118.1-2011 “IEEE Standard for Synchrophasor Measurements for Power Systems”, 2011.

[14] IEEE Std C37.118.2-2011 - IEEE Standard for Synchrophasor Data Transfer for Power Systems.

[15] Swissgrid Website: https://www.swissgrid.ch/swissgrid/en/home/reliability/wam.html;

[16] I. Nedelcu, I.P. Viziteu, F. Balasiu, A. Miron, “From the wide area monitoring to the wide are protection in the Romanian power grid”, CIGRE General Meeting, Paris, 2010.

[17] F. Balasiu, F. Lazar, “Improve Power System Operation Through Synchrophasor Applications”, WEC Regional Energy Forum, 13-17.06.2010, Neptun-Olimp, Romania.

[18] UCTE, Final Report of the Investigation Committee of the 28 September 2003 Blackout in Italy, April 2004.

[19] UCTE, Final Report System Disturbance on 4 November 2006.

5. List of Figures

6. List of Abbreviations

AGC	Automatic Generation Control
aFRR	automatic Frequency Restoration Reserve
CNPP	Cernavodă Nuclear Power Plant
EMS	Decentralised energy management system
DER	Distributed Energy Resources
DMS	Distribution Management System
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
GPS	Geographic Positioning System
GUI	Guide User Interface
HMI	Human Machine Interface
HV	High Voltage
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineers
NIST	National Institute of Standards and Technology
PDC	Power Data Concentrator
PMU	Phasor Measurement System
PSA	Power System Analysis
RoCoF	Rate of Change of Frequency
RoCoP	Rate of Change of Power
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SDH	Synchronous Digital Hierarchy
SMX	Smart Meter eXtension
SO	System Operator
SoA	State of the Art
TCP	Transmission Control Protocol
TO	Transmission Owner
TSO	Transmission and System Operator
UDP	Used Datagram Protocol
UPB	University Politehnica of Bucharest
USM	Unbundle Smart Meter
VPP	Virtual Power Plant
WAMS	Wide Area Measurement system
WAMCS	Wide Area Measurement and Control system
WAMCPS	Wide Area Measurement, Control and Protection system
WP	Work Package
WPP	Wind Power Plant

Annex A. Wide area measurement system (WAMS) in the Romanian power system

In 2009, a synchro-phasors based Wide Area Measurement System (WAMS) was implemented by Transelectrica in the Romanian power system to record and archive the metered data. All equipment was provided by Schweitzer Engineering Laboratories (SEL) [8][9].

The Romanian WAMS consists of 15 phasor measurement units (PMUs) connected to the buses of most important 400 kV substations, and a central server. The PMUs are located in the substations on the interconnection lines, and in nearest substations to very large generating units, as shown in Figure A.1. On the interconnection lines, there are 8 PMUs installed at Rosiori, Nadab, Arad, Portile de Fier I, Tantareni, Rahman, Stupina, and Isaccea. The other 7 PMUs are installed in the following substations: Cernavoda, Mintia, Iernut, Brasov, Gutinas, Bucuresti Sud, and Domnesti. These include also a few wind power plants (WPP) for islanding detection.

In 2013, the systems located on the 8 interconnection lines were upgraded with additional equipment to perform a power oscillations monitoring. This application requires an accurate time synchronization of all databases. For this reason, the time error is less than 500 ns.

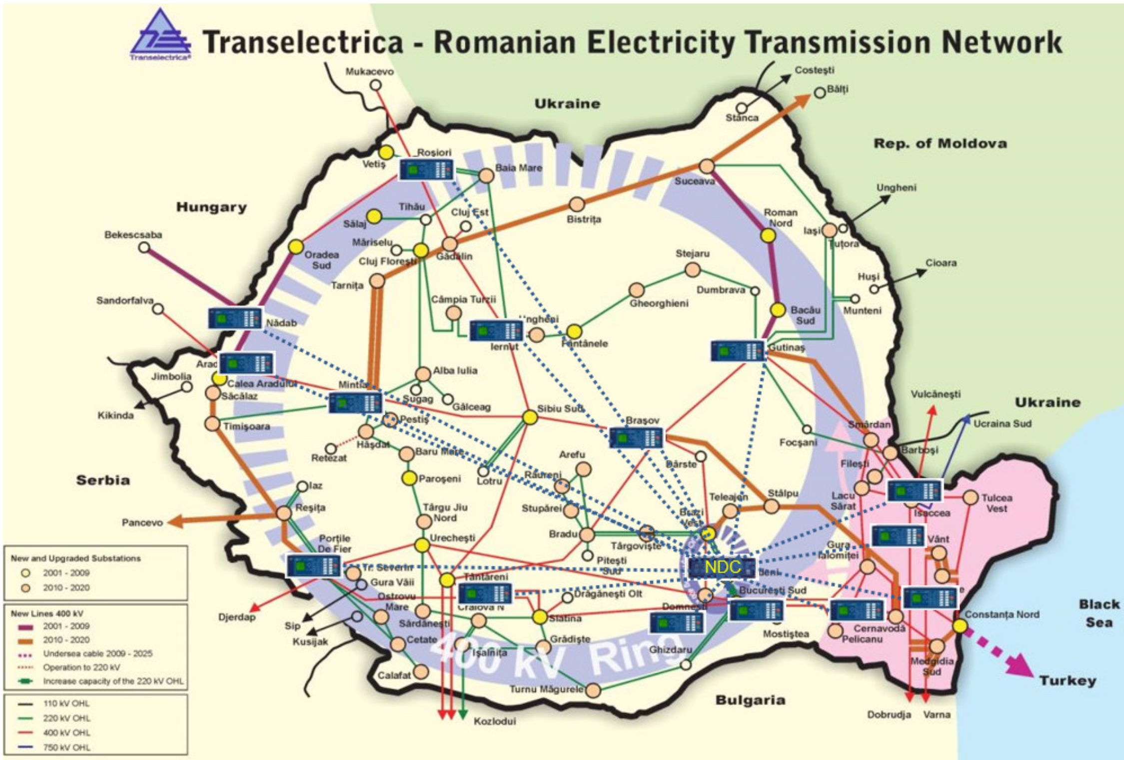

Figure A. 1 PMU locations in Romania [5][10].

The *hardware architecture of the WAMS* in Romania is shown in Figure A.2.

The 8 local equipments located in power substations of the interconnection lines consist of the following devices:

- the measurement devices (SEL-451 and SEL-451-5); these are the PMU devices that collect current and voltage raw data from the measurement transformers and converts them into phasor data;
- a Power Data Concentrator (PDC) (SEL-3373) for archiving the local data metered by the PMUs.
- a Satellite Synchronized Clock (SEL-2407) that provides the time stamp to the set of measured data;

- an Ethernet Switch (SEL-2725) and a fibre optic media converter (LAN/WAN) for transferring data to the central server.

The other 7 local equipment consist of the PMU, the Satellite Synchronized Clock [11], and the Ethernet Switch. There is no local data archiving. All packages of data are directly sent to the central server.

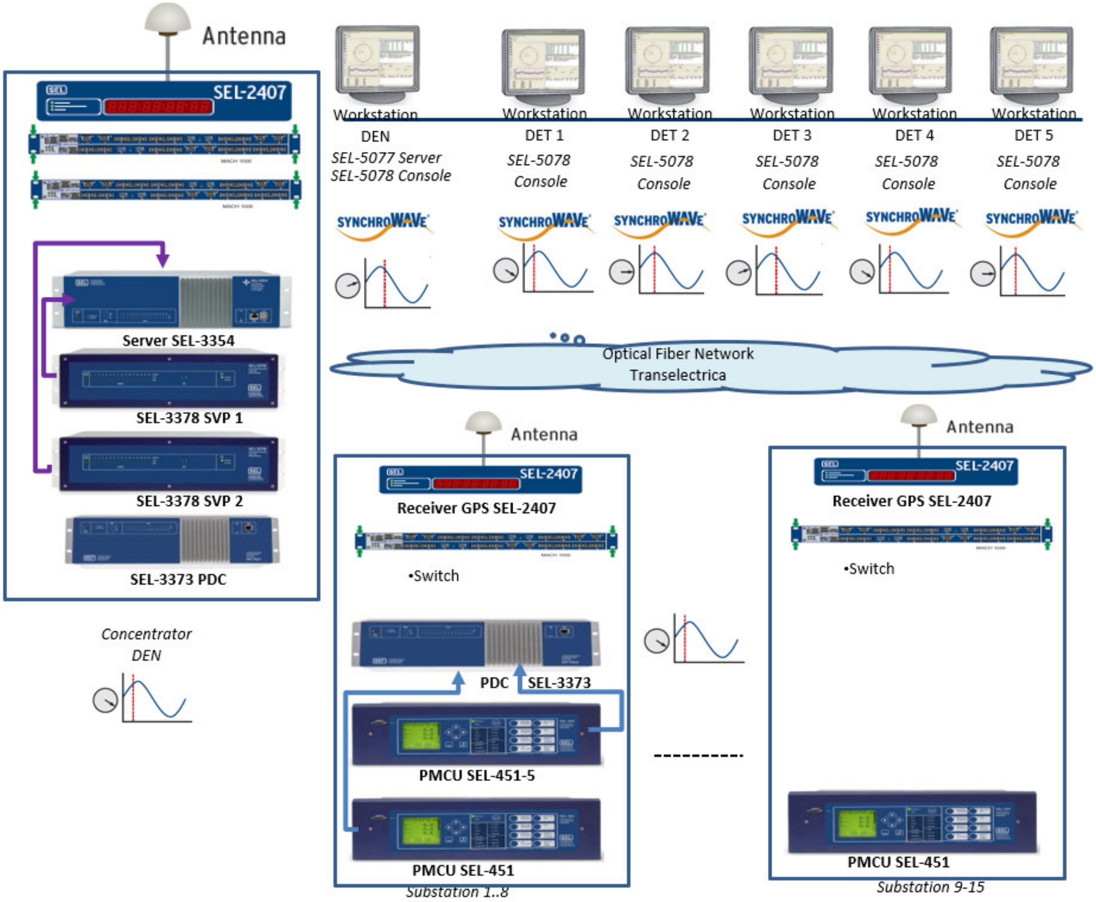

Figure A. 2 Hardware architecture of the WAMS in Romania.

All data can be visualized, using the application called SynchroWave [12], at any of the 6 dispatching centres, the central one located in Bucharest (denoted as DEN), and the five regional centres (denoted as DET).

The *architecture of the central system*, located at DEN (Figure A.2), is based on the Central Synchrophasor[1] Processor (CSP). It collects data reported by the 15 PMUs via the corresponding local PDCs via Ethernet. In addition, it communicates with two Synchrophasor Vector Processors (SVP), a software environment based on SEL-3378. The SVP correlates (by time alignment) the synchrophasor messages, processes them with a programmable logic engine, and sends control commands to external devices to perform user-defined actions. The SVP also sends data to devices such as other SVPs, phasor data concentrators (PDCs), and monitoring systems. The SEL-3373 PDC can concentrate as many as 40 PMU inputs at rates up to 240 messages pes second, (exceeding for example the recommendations in IEEE C37.118-2011 standard [13][14], i.e. 30/25 frames per second).

The data analysed by the CSP can be displayed using real-time visualization software either at the National Dispatch Centre (DEN in Romanian) or at one of the five Territorial Dispatch Centres (DET in Romanian), as shown in Figure A.2. The software, called SynchroWave, offers: automatic detection of transients due to RES-based, power electronics controlled, electricity generation; power system insight beyond SCADA capabilities, with a high time granularity of

[1] Synchrophasor is an alternative term for synchronized phasors.

information (up to 60 frames per second), chronology and propagation path of system events with instant access to real-time and historical data; improved operator situational awareness providing phase angle difference measurements across key transmission lines, as shown in Figure A.3 [15].

It also offers different communication possibilities that are not included in the sychrophasor's processor (SEL 3378), like dial-up or rented line connections. It is user-friendly, with dockable windows and multiple displays that give operators and engineers the flexibility to create customized visualizations to optimize their ability to monitor the power system.

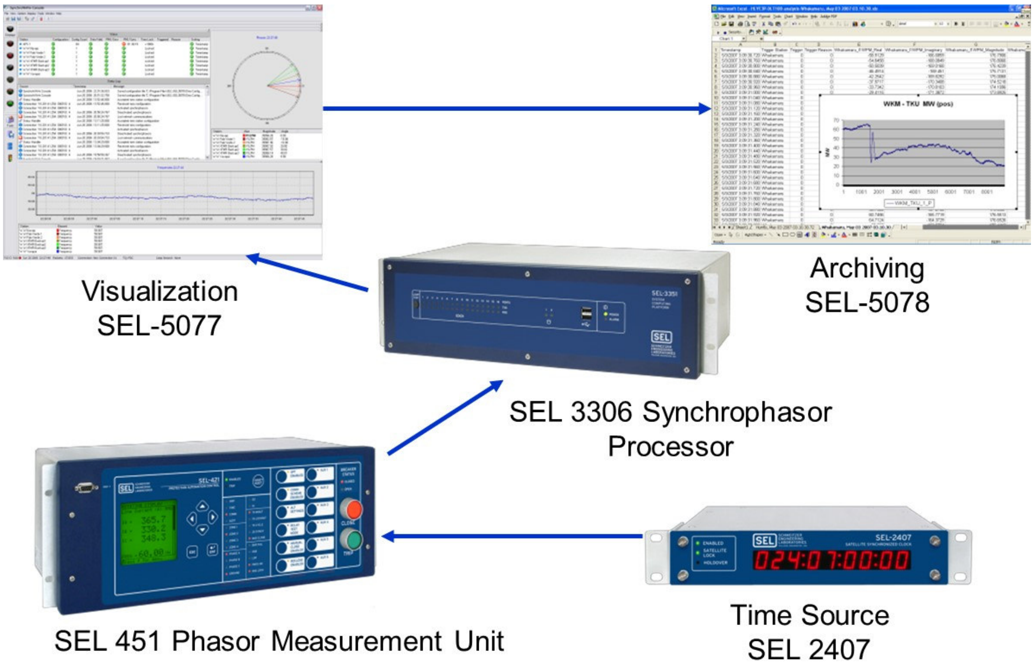

Figure A. 3 Syncrophasor monitoring and analysis.

An example of the variable structure that can be collected from the PMU, in both polar and Rectangular coordinates, as it is shown in Figure A.4. The WAM system implemented in the Romanian power system includes a software dedicated to both real time monitoring and post-event analysis. The aim of the PMUs installed on the interconnection lines is to provide power flow data calculated based on the primary data, i.e. voltage magnitudes, voltage angles, current magnitudes, and current angles [8].

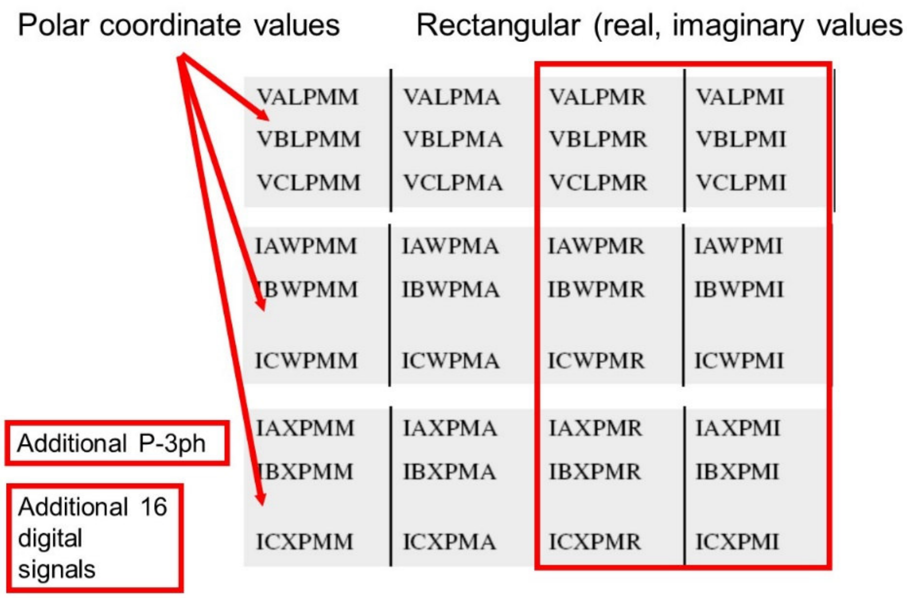

Figure A. 4 Example of data format of the synchrophasor measurement SEL 451.

Thanselectrica is planning to extend the WAMS with new applications, such as [8][16][17]:

- wide area monitoring and alarm for limits violations;
- islanding operation detection;
- wide area disturbance analysis;
- real time control;
- dynamic power system performance indication;
- load shedding;
- accurate pole slip detection;
- improve state estimator accuracy.

Annex B. Critical events recorded in the Romanian power system

B.1 Frequency analysis in the case of sudden disconnection of a 700 MW nuclear unit

The Cernavoda Nuclear Power Plant (CNPP) is one of the largest power plants in Romania, after the Rovinari and Turceni coal-fired power plants. The main information needed in order to understand its importance in the Romanian power system is:

- it shares 17-19% of the total generation in Romania (see deliverable D5.6);
- consists of two units, each being 700 MW rated;
- the auxiliary services account for about 50 MW, which represents about 7% of the rated power;
- usually it is operated at maximum power;
- does not participate to frequency control by providing balancing energy; basically, the plant is used to cover base load, based on long-term contracts;
- each generation unit is inherited with a mechanical inertia constant of 7.3 MWs/MVA, as compared to 2.9 MWs/MVA specific to the inertia constant of a hydro-power plant. The inertia constant of the CNPP is even largest than the one found in coal-fired generation units.
- Taking into account the above information, the total mechanical inertia constant, available in the two NPP units at Cernavoda, accounts for about 40% of the total mechanical inertia available in Romania;
- It is located on the banks of the Danube river, in the Dobrogea region (blue circle in Figure B.1). Dobrogea region is characterized by a large generation excedent because of the 2600 MW installed in wind power plants, representing 80% of the total wind power installed in Romania.

Figure B. 1 Location of CNPP on the map of Interconnected Network of Continental Europe.

The CNPP is provided by two PMUs owned by Transelectrica. Because of the critical importance of CNPP and the presence of wind power in Dobrogea, several PMU are available in the Dobrogea region, as shown in Figure B.2.

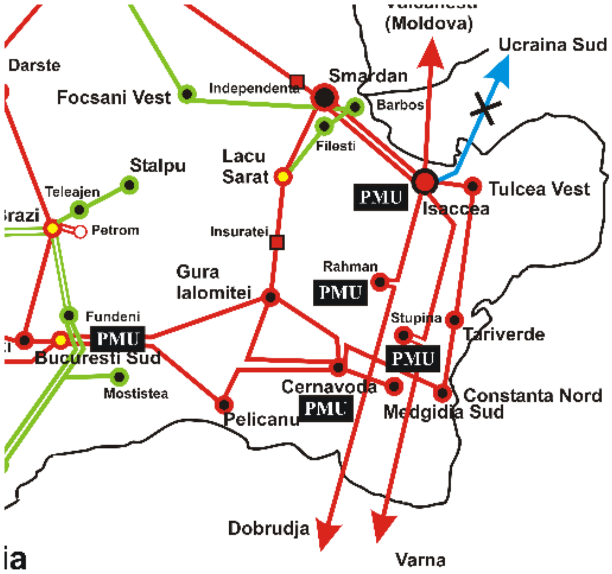

Figure B. 2 Zooming on the CNPP area of the Romanian power system.

It is expected that in the transition towards clean energy or 100% renewables, nuclear energy is an option for countries with low wind and or solar resources, and that are relying currently on coal-fired power plants. This is why understanding the importance of CNPP for the Romanian power system is very important to understand the actual operation of the Romanian power system and the Interconnected Network of Continental Europe.

During the measurements campaign performed by Transelectrica, two major events have been recorded, with very important results for the RESERVE project in terms of the frequency behaviour. The initial conditions and the characteristics of the events are as follows.

CNPP_ev1:

- Occurred on June 1st 2017, at 00:35 CET
- One generation units was out of service, under planned maintenance
- The disconnection was sudden. Only fast plant controls were activated
- The wind accounted for 18% of the total generation;
- 17% was the power export of the Romanian power system at the instant of the event occurrence;

CNPP_ev2:

- Occurred on August 16th 2018, at 16:56 CET;
- Both generation units were in operation;
- The disconnection was sudden. Only fast plant controls were activated;
- The wind accounted for 4.4% of the total generation;
- 6% was the power export of the Romanian power system at the instant of the event occurrence;

The export and the total generation from wind could be less important under the interconnected operation of the Continental Europe.

The frequency variation at all the buses provided with PMUs in the Romanian power system during the two events is shown in Figures B.3 and B.4.

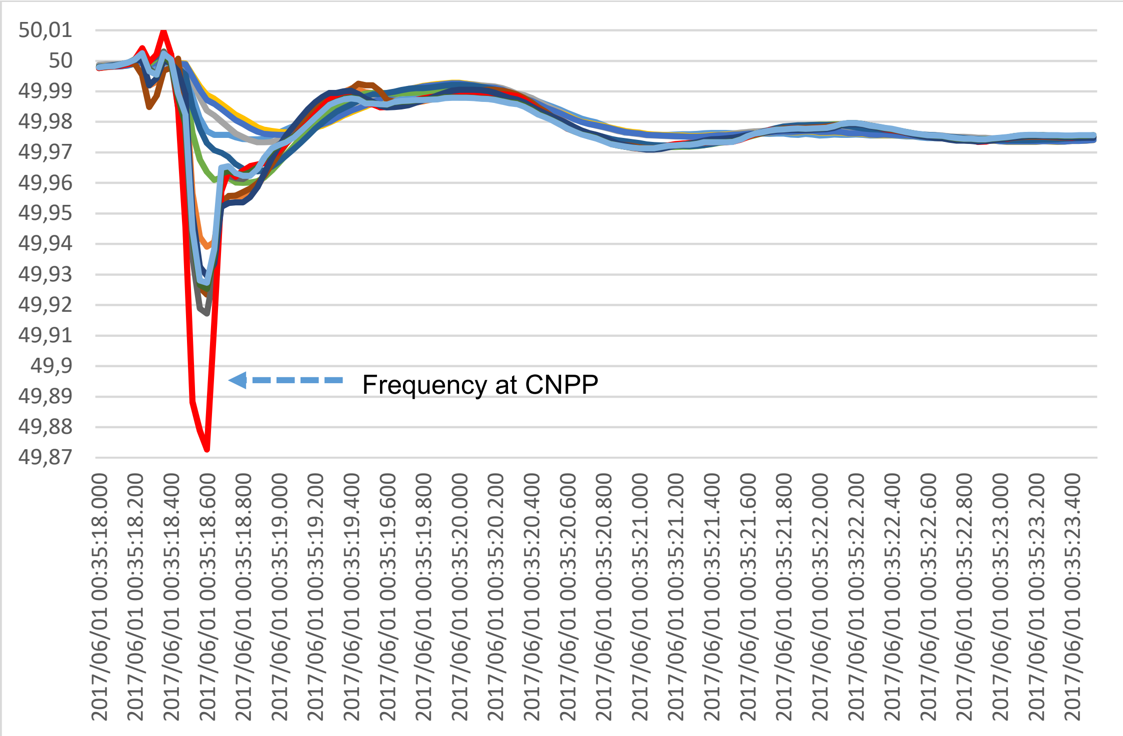

Figure B. 3 Frequency response in the Romanian power system during CNPP_ev1 on June 1st 2017.

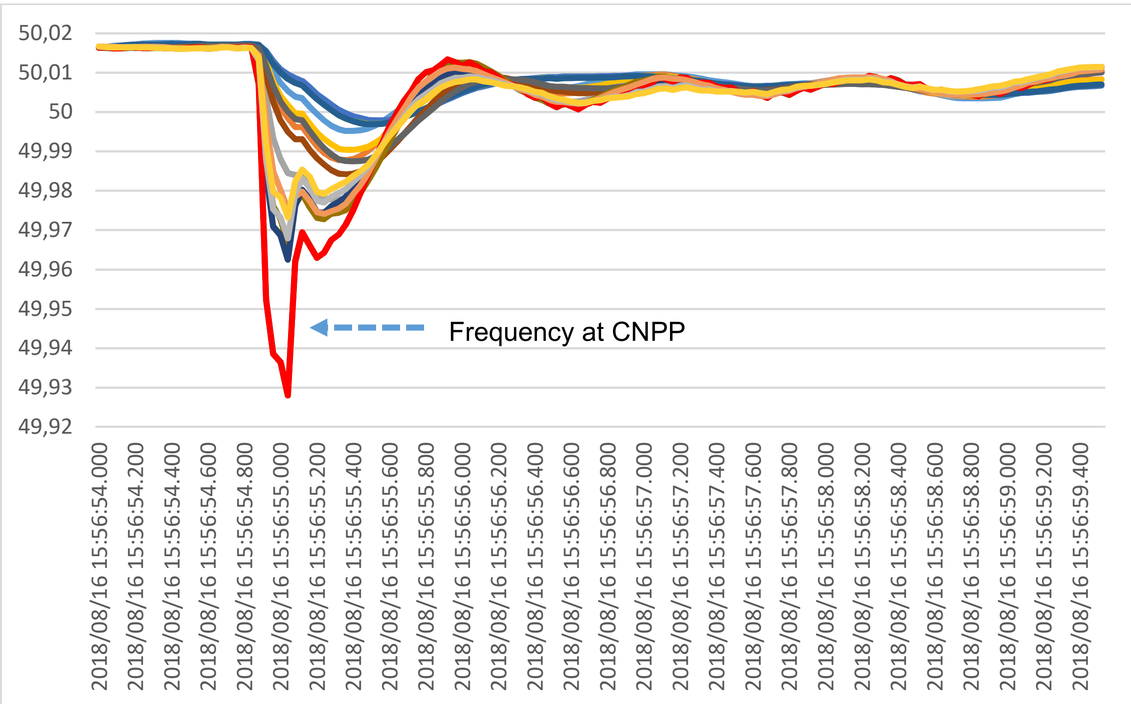

Figure B. 4 Frequency response in the Romanian power system during CNPP_ev2 on August 16th 2018.

Following the loss of one generation unit during CNPP_ev1, the frequency nadir was 49.87 Hz on the 400 kV busbar of the CNPP. The frequency nadir at all the other 400 kV busbars provided with PMUs is higher; the longer the electrical distance between CNPP and the other 400 kV buses, the small was the frequency dip. The smallest frequency variation was eventually 20 mHz at Arad (one of the most Western point in the Romanian power system).

The frequency nadir recorded during CNPP_ev2 was 49.93 Hz on the 400 kV busbar of the CNPP, half pf the value recorded during CNPP_ev1. Again, the frequency nadir recorded by all the other PMUs are higher, eventually much higher, then the one recorded at CNPP. The frequency recorded in remote buses, which are located electrically and geographically towards the Interconnected Network of the Continental Europe, experienced very small variations; this is because of the strong mechanical inertia located Western of the Romanian power system. The initial frequency during CNPP_ev2 was around 50.02 Hz, higher than the initial frequency recorded during CNPP_ev1. For all these reasons, the frequency recovered very fast (1.2 seconds) around the reference frequency (50 Hz).

In both cases, the main inertial response was observed during the first 1.2 seconds after the perturbation inception, within which the frequency was restored around a quays-steady state value. The total transient period was around 5-6 seconds, specific to the mechanical inertial response.

For better understanding of the magnitude of the two events, we have overlapped the frequency graphs recorded during the two events. The time synchronization is not important because the different time conditions of the two events. Figure B.5 shows that the frequency variation during CNPP_ev1 was two times deeper than during CNPP_ev2. This is explained by the facts that during CNPP_ev2 half of the total mechanical inertia available at CNPP was still available.

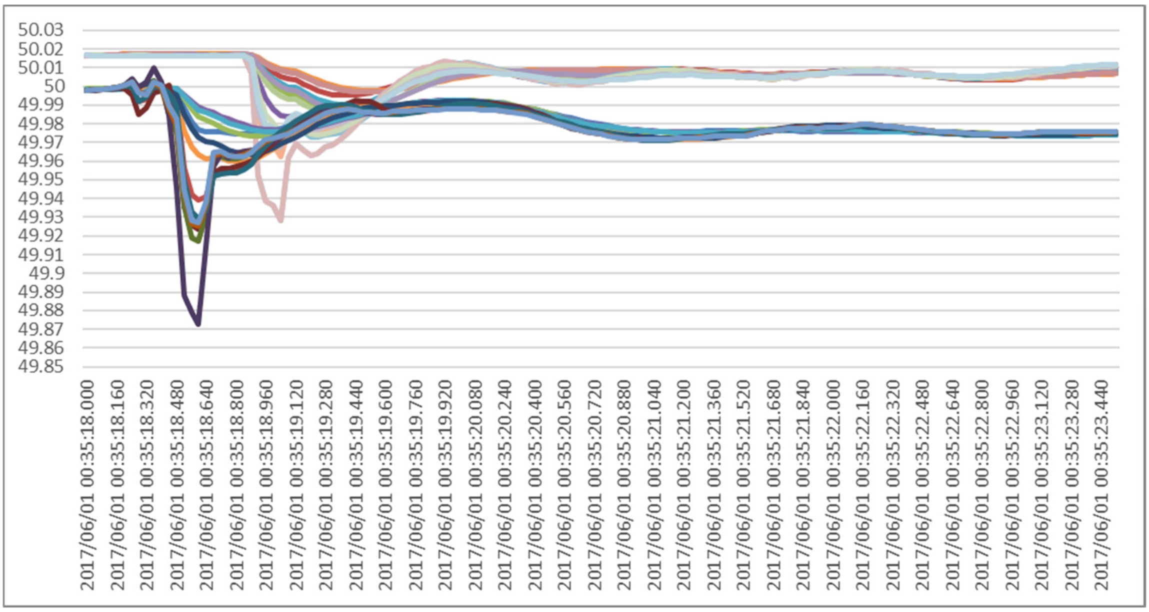

Figure B. 5 Frequency variation during CNPP_ev1 and CNPP_ev2.

Under the actual conditions of the Interconnected Network of the Continental Europe, in both events experienced by CNPP the system recovered very quickly after the perturbation and maintained the frequency stability. However, there are a few conclusions to draw from these observations, i.e.:

- The loss of important mechanical inertia leads to large frequency excursions. The most important variation occurs in the first 200-500 milliseconds. This time is important to propose calculation of RoCoF or RoCoP for the very fast controls.
- The largest mechanical inertia is available in nuclear units. This inertia is visible locally. Even if only one unit was disconnected at CNPP, the availability of only half of the total mechanical inertia caused the frequency dip to be double. The location on the edge of the CNPP is also an explanation for this behaviour. However, in the case that CNPP will be dismantled, while the power installed in wind generation is significantly increased in Dobrogea, the lack of mechanical inertia could cause frequency instability and local oscillations.
- The two events are specific to a fast-transient behaviour. The loss of a large nuclear unit can be classified as large perturbation. Due to the strong interconnection of the Interconnected Network of the Continental Europe, the frequency was recovered very

fast, first by the intervention of the inertial response, then following the contribution of the frequency containment control.

B.2 Frequency analysis in the case of lines tripping followed by loss of generation

This case aims at analysing the impact on the frequency in the Romanian power system following by the loss of coal-fired generation units. These generation units, from the Turceni and Rovinari power plants, are connected to the 400 kV buses Tantareni and Urechesti, as shown by dashed ellipse in Figure B.6.

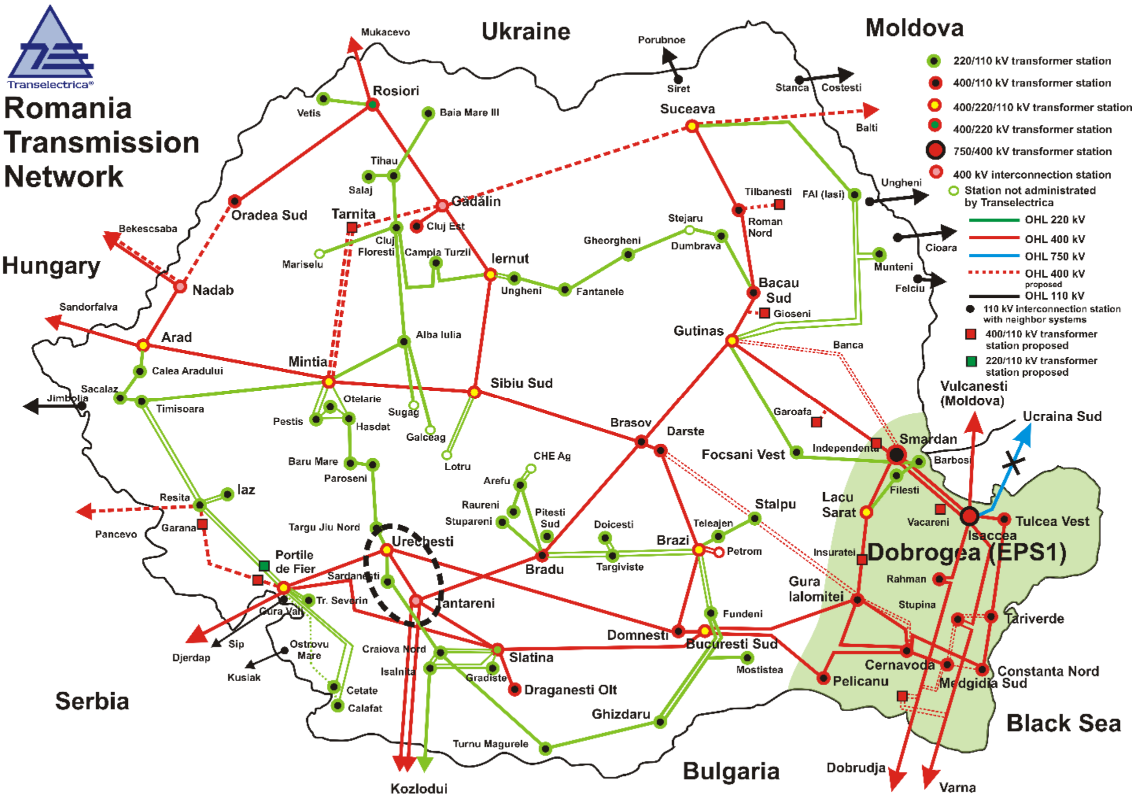

Figure B. 6 Geographic location of the main coal-fired power plants in Romanian power system

Figure B.7 shows a screenshot of the generation-load curves in the Romanian power system on July 12th 2017. Following severe meteorological conditions, consisting of three consecutive thunder strikes on the transmission lines, about 1000 MW were lost. Coal-fired power generation was lost at Turceni and Rovinari. This is observed at the black line by the sudden reduction of the generation value. At the same time, rapid variation is observed to the power exchange ("Sold" in Romanian). The power exchange was quickly restored to the initial value following the fast deployment of balancing reserves available in hydro units.

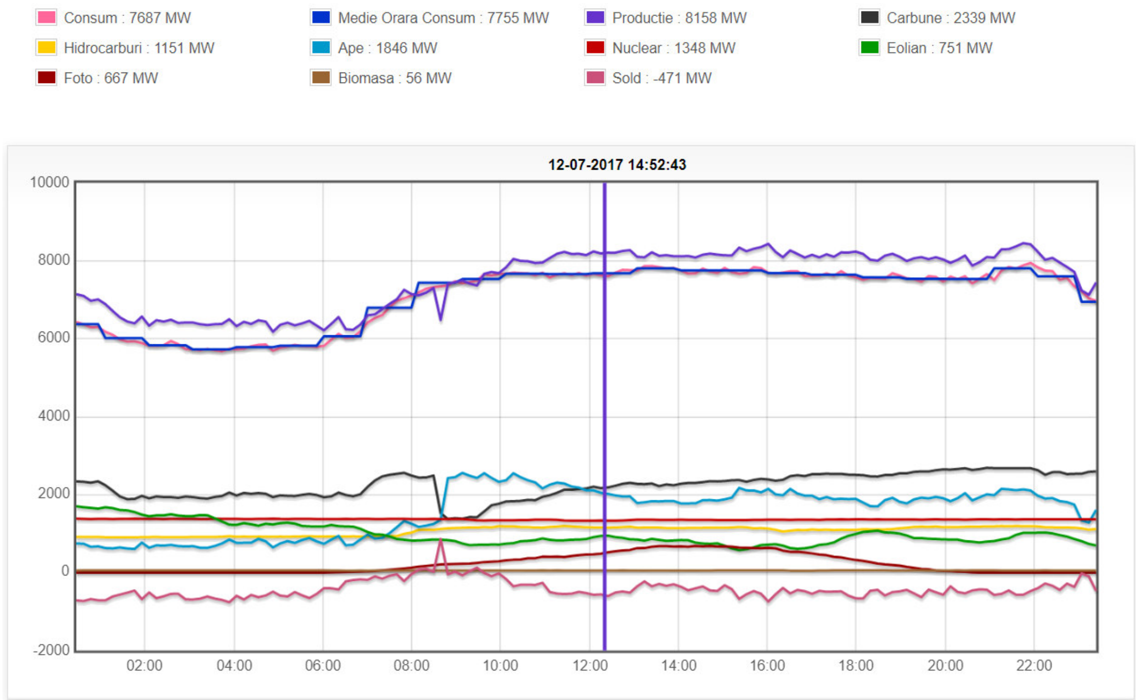

Figure B. 7 Snapshot of generation-load curves on July 12th 2017 in the Romanian power system (www.transelectrica.com).

The fast frequency control was properly activated, and the 1000 MW unbalance was cancelled out by using balancing reserves available in the hydro units, as shown by the blue line in Figure B.7. The loss of power generation lasted for about 10 minutes, whereas the balancing using hydro reserves was done within 8-9 minutes.

Figure B.8 shows the frequency variation at all the 400 kV buses from the Romanian power system provided with PMUs. Before the incident, the frequency was around 49.8 Hz, then, after the perturbation, the frequency exhibited ups and downs between 49.92 Hz and 49.97 Hz for at least 10 minutes.

The graphs in Figure B.8 are similar to a low reporting rate of the PMU and does not reveal details on transient phenomena of the electrical machines attached to the 400 kV buses. Figures B.9 and B.10 shows a zooming on the tree consecutive incidents (short-circuits) caused by meteorological conditions. We have focussed on four network buses remotely located, two near the short-circuits location, and two in opposite directions, at larger electrical distances that may exhibit interarea or local power oscillations (observed here only by using PMU measurements).

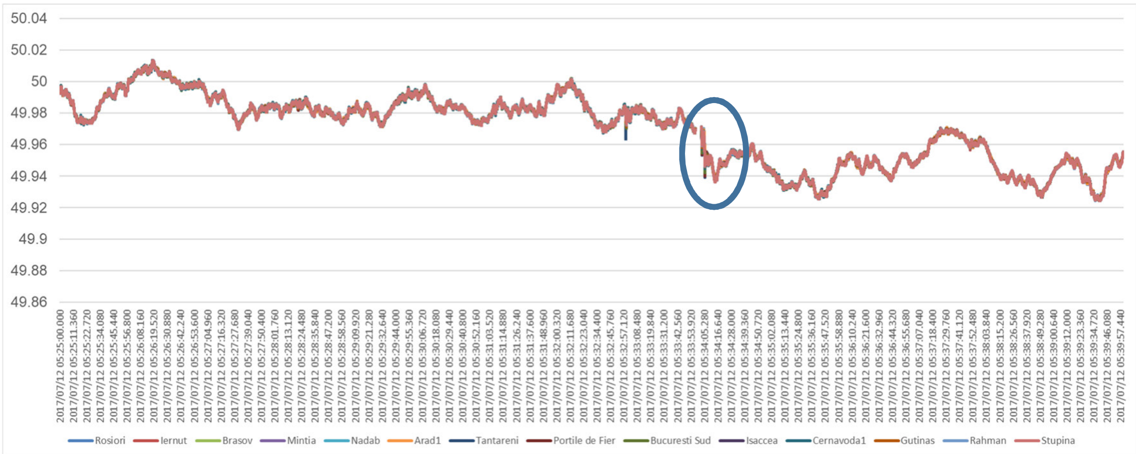

Figure B. 8 Frequency variation during 15 minutes around the perturbation that occurred on July 12th, 2017, in the Romanian power system.

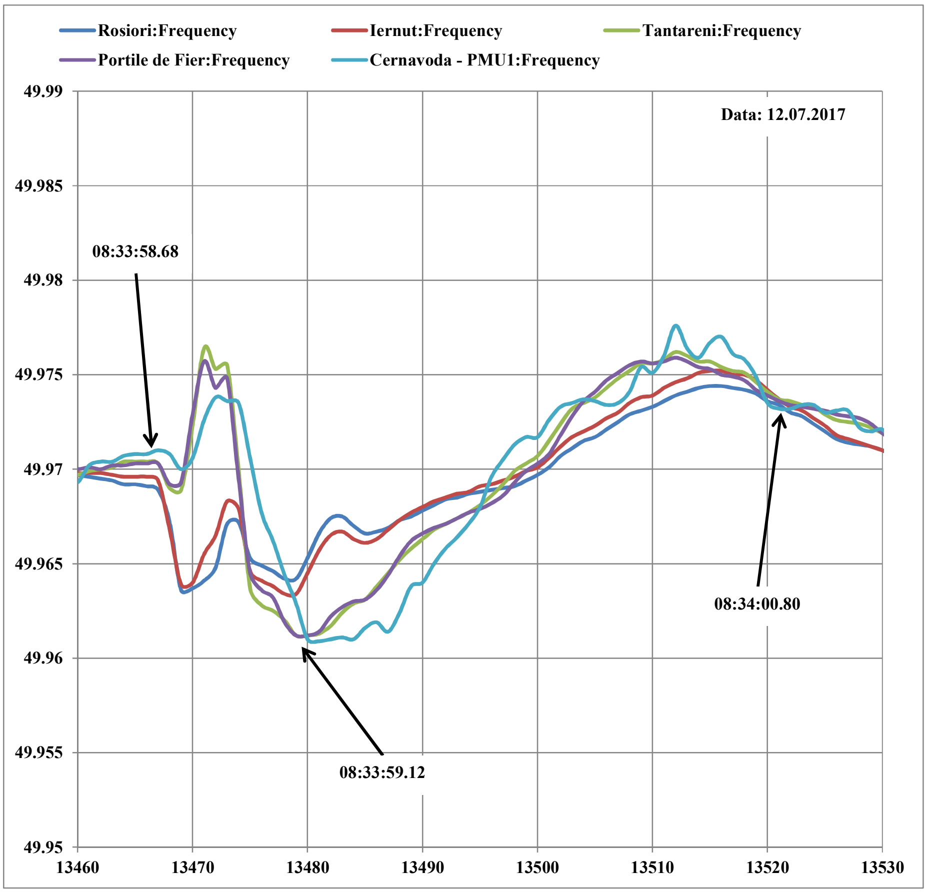

Figure B. 9 Zoom on the frequency variation following the inception of the three short-circuits on July 12th, 2017, in the Romanian power system (time of the incident is the local time).

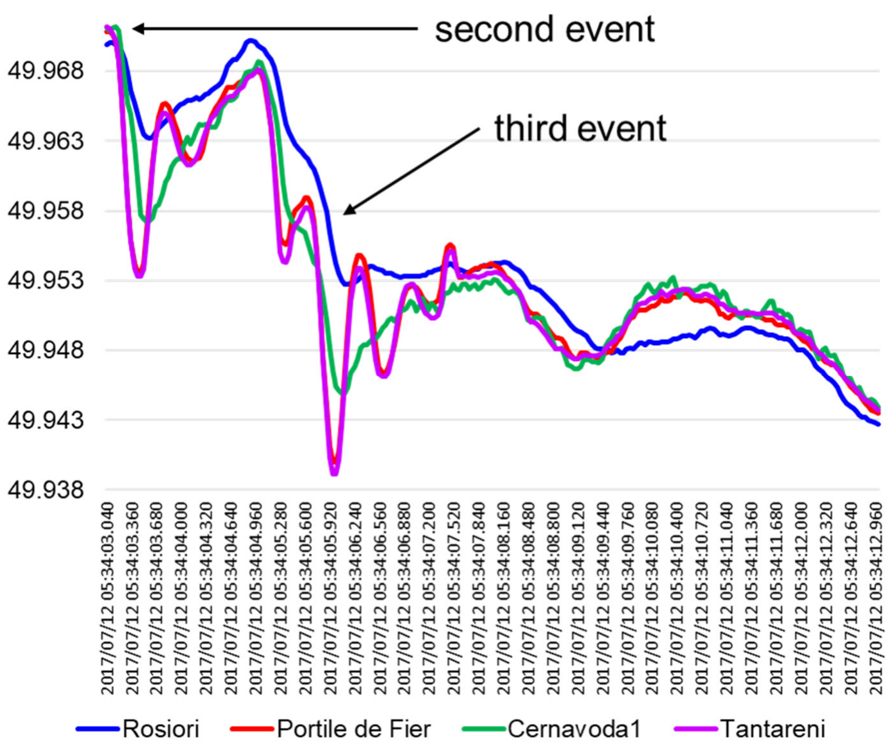

Figure B. 10 Zoom on the frequency variation during the perturbation on July 12th, 2017, in the Romanian power system (time of the incident is the UCT).

The importance of the PMU measurements is observed in both figures as transient phenomena can be clearly analysed. The following conclusions can be drawn:

- The frequencies metered at the two buses found in proximity (Portile de Fier and Tantareni) exhibit synchronized variations, which means that the power plants attached to these buses are swinging together. Their oscillations are quickly damped showing inheritance of mechanical inertia. Of course, the two buses accommodate two large power plants, one 1150 MW hydro power plant and two coal-fired power plants totalling about 3400 MW in available units. The importance of the mechanical inertia here is obvious for frequency stability.
- Figure B.9 exhibits opposite frequency oscillations that reveals temporary desynchronization between remote generators, which means that the generators are oscillate against each other. The generators are quickly synchronized, within 2 seconds, thus starting to swing together, due to the strong interconnection of the Romanian power system and to the mechanical inertia inherited in generation units located near the faults location.
- The frequency at the 400 kV bus in Cernavoda exhibits high-variation oscillations, which is visible after each event. The same occurs at the other extreme of the Romanian power system at the Rosiori bus, but with lower magnitude. The oscillations reveal the attempt of the control systems attached to the generation units accommodated at the two buses to maintain the synchronism and stability.
- The second and the third events do now exhibit opposite oscillations. This is probably because of modified network architecture or the duration of the fault.
- The frequency nadir in this case is smaller than the frequency nadir presented in appendix B.1, probably because of the much larger mechanical inertia inherited in the power plants located in the proximity of the fault location.
- The most severe perturbation in a power system is the short-circuit. Although the same operating conditions cannot be recreated in a simulation because of the very large number of information, close conditions are worth to be considered for simulation in order to compare the results that be achieved by simulations with those from a real system. The actual power system is characterized by large mechanical inertia and less renewable energy sources. This is why, simulation of future characteristics of the power system will reveal different results than those obtained from real measurements.
- The use of synchronized measurements by means of PMU are very important for developing wide area monitoring systems because they help capturing very fast dynamics, which is useful un analyse and understand the behaviour of the interconnected power system in real conditions. Direct concussions by experts help taking decision without performing off-line simulations.

Annex C. Frequency analysis during a major event in Europe on January 10th, 2019

The benefits of the interconnected operation of the power systems from the Continental Europe have been demonstrated since the beginning of the creation of the ENTSO-E system (former UCTE and UCPTE, respectively). Currently, the Interconnected Network of the Continental Europe spans from Portugal to Turkey and from Denmark to Italy. Operational grid codes have been developed by ENTSO-E in order to ensure the stable operation of the entire system. However, the history shows that even under clear and written operation codes, the ENSTO-E system is continuously subjected to challenges that can make the system to become unstable.

Before starting the analysis we need to highlight the causes of two major disturbances that occurred in the ENTSO-E system, that is:

- **The Major grid blackout of the Italian power system, on 28 September 2003[18].** The sequence of events was triggered by a trip of the Swiss 380 kV line Mettlen-Lavorgo at 03:01 caused by tree flashover. There was cascade of events consisting in successive disconnection of the Italian interconnection lines until 3:25:34 when the Italian power system was separated from UCTE by the disconnection of the last remained interconnection line.
- **The desynchronization of the ENTSO-E Continental Europe, on 4 November 2006** [19]. On the evening of November 4th, 2006, there were significant East-West power flows as a result of international power trade and the obligatory exchange of wind feed-in inside Germany. These flows were interrupted during the event. The tripping of several high-voltage lines, which started in Northern Germany, split the UCTE grid into three separate areas (West, North-East and South-East) with significant power imbalances in each area. The power imbalance in the Western area induced a severe frequency drop that caused an interruption of supply for more than 15 million European households.

On 10 January 2019, 21:02 CET, a new critical situation was registered in the Continental Europe power system. The frequency dropped to 49.8 Hz (compared to 49.0 Hz in 2006) for nine seconds, which is the largest absolute frequency deviation since 2006.

The German company Next Kraftwerke GmbH[2], a VPP operator, has recorded the frequency during a time window around the duration of the abnormal variation of the frequency.

Figure C. 1 Frequency recorded in Cologne/Germany on January 10th.

[2] https://www.next-kraftwerke.com/energy-blog/who-is-disrupting-the-utility-frequency

According to Next Kraftwerke GmbH, there has been three important instants, marked by the following point in Figure C.1:

- Point 1 - the failure at the Spanish coal plant Litoral, which marks the beginning of the grid frequency disruption.
- Point 2 - the failure of the Penly 2 reactor at the nuclear power plant near Dieppe in France. The grid still manages to cover these shortfalls.
- Point 3 - the pumps at Goldisthal Pumped Storage Station (Germany) kick in. At this point, the situation in the grid was already unstable, and the frequency drops rapidly – until France's RTE calls for 1,500 MW of rolling blackouts. TSOs in Germany react as well, calling on emergency reserves including 153 MW from the pumped-storage hydro plant Herdecke near Dortmund.

The frequency was also recorded by the website www.mainsfrequency.com[3] which is specialized in metering and providing services by PMU measurements related to power system frequency. The graphs presented in Figure C.2 was obtained by means of a PMU located also in Cologne/Germany. This figure shows that the frequency dropped by about 200 mHz at hours 20:02.

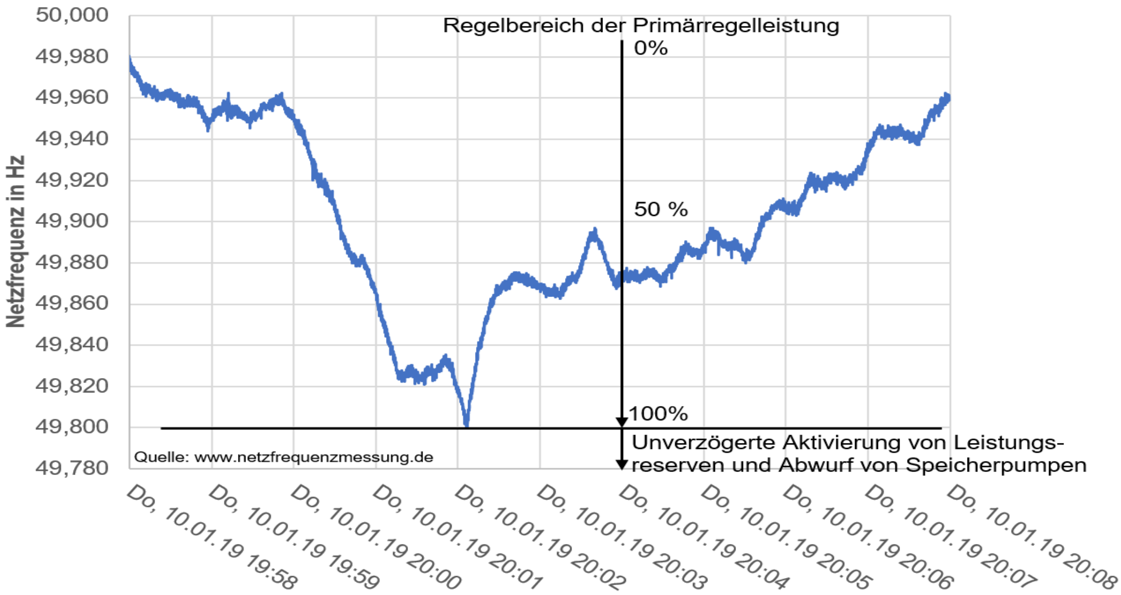

Figure C. 2 Frequency recorded by www.mainsfrequency.com on January 10th.

On 28.05.2019 ENTSO-E[4] published an intermediary report of its investigation on the incident that occurred on January 10th, 2019. The report reveals that the voltage drop was caused by the superposition of a large deterministic frequency deviation on one hand, and another frequency deviation, due to a frozen measurement on four interconnection lines between Germany and Austria that lasted between 9 and 11 January, on the other hand.

Also, ENTSO-E is analysing is the permanent long-lasting deviation of the Serbia, Macedonia and Montenegro (SMM) control block - which covers Kosovo - also affected the frequency; this concern is raised following the unbalance in SMM that caused a delay by 6 minutes[5] due to the underfrequency operation for several weeks. This time, however, it is known also that, the SMM control block did not participate in the large frequency deviation at 21:02 on 10 January as the EMS (Serbian TSO) Control Centre observed the low frequency and took preventive action and

[3] https://www.netzfrequenzmessung.de/aktuelles.htm#2019_01

[4] https://docstore.entsoe.eu/Documents/News/2019/190528_frequency_deviations_FAQs.pdf

[5] https://www.entsoe.eu/news/2018/03/06/press-release-continuing-frequency-deviation-in-the-continental-european-power-system-originating-in-serbia-kosovo-political-solution-urgently-needed-in-addition-to-technical/

did not disconnect, as planned, a 300 MW pump-storage unit that was running in generation mode.

Despite this frequency drop, ENTSO-E states that the emergency frequency range was never reached, and the security of supply was never endangered.

This frequency variation reveals a totally different phenomena compared to the two cases presented in Annex B. The frequency variation was slow over the Romanian power system, similar to the Intercontinental Network of the Continental Europe. The purpose was to analyse, for such a behaviour, if there are differences in the frequency value first between the measurements of the 15 PMUs located in the Romanian power system, then if there are differences between frequency in Romanian and frequency in other countries.

Figure C.3 shows the frequency recorded in Romania for about 20 minutes. We have marked by vertical dashed lines the instants of important changes. The central line marks the lowest value frequency, which is 200 mHz, similar to that recorded in Germany. The most important instant that triggered the frequency to drop occurred 6-7 minutes before the frequency nadir shown in Figure C.3, the frequency was gradually recovered.

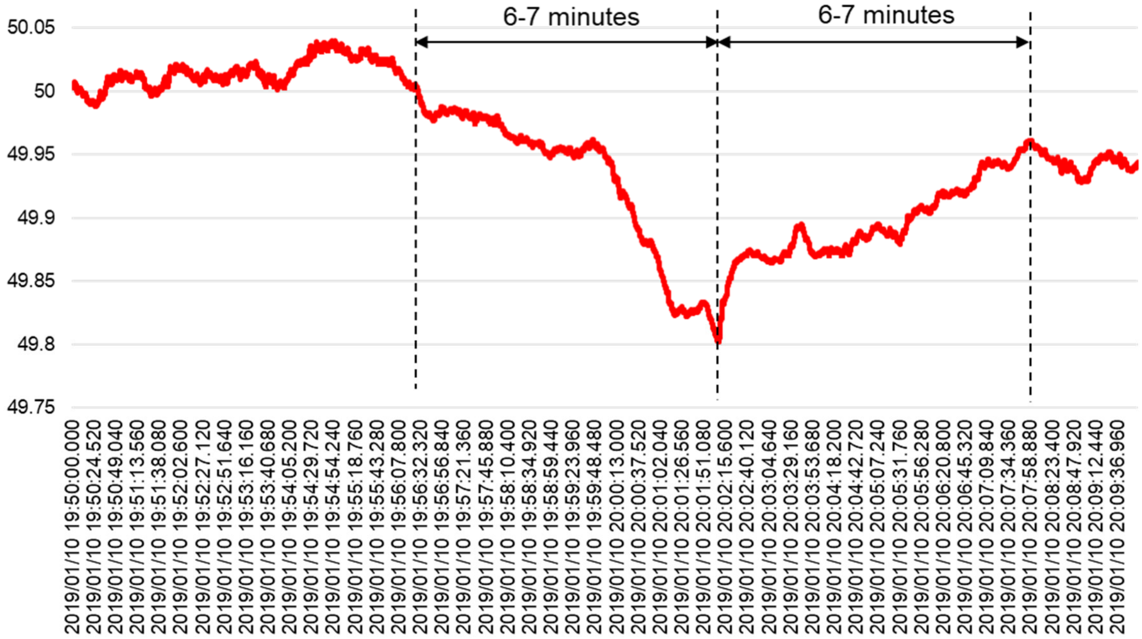

Figure C. 3 Frequency variation on January 10th, 2019, in Romania (time is UCT Time).

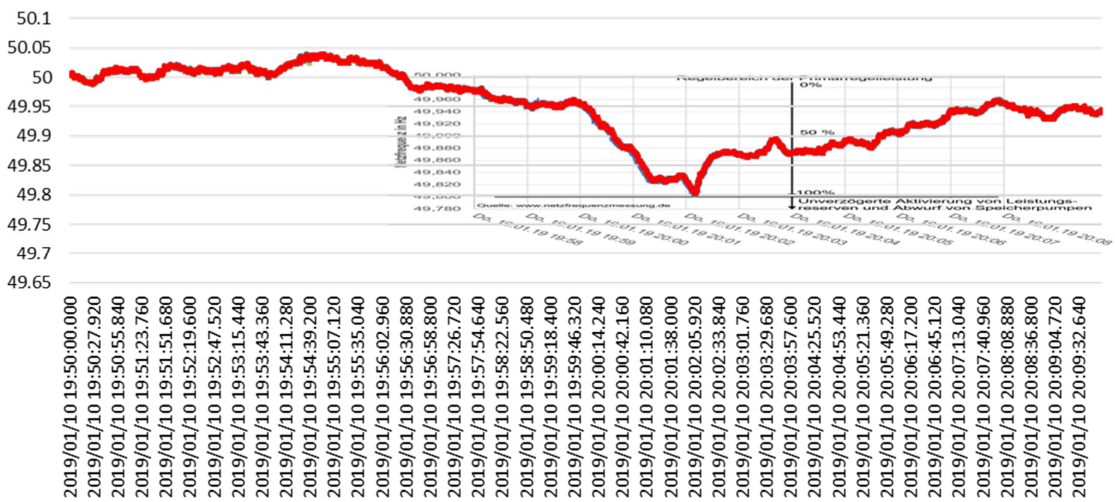

Figure C. 4 Overlapping of the frequencies metered in Germany and Romania.

Note that all the frequency measurements made with the 15 PMUs that form the WAMS of Transelectrica match almost perfectly. The frequency curve in Romania was compared with a frequency curve metered in Germany (see Figure C.4).

The frequency was almost identical in both Germany and Romania showing that, under the current operating conditions of the European Continental power system, with ample mechanical inertia available across the system, the generators maintain synchronism with each other. This experience encourages us to support proposals for better monitoring of power flows across Europe. An extended monitoring across Europe helps us to observe how strong the synchronization between generators is by comparing the frequency values in remote points. This is useful to understand the behaviour of the power system in terms of frequency variation at different levels of the mechanical inertia.

We have therefore expanded our analysis by comparing PMU data from Romania, Germany, France and Italy, as depicted in Figure C.5. All points are, therefore, located in the interconnected network of Continental Europe. While the PMUs from Romania are commercial systems, all the other PMUs used are prototype low-cost devices found in their test phase.

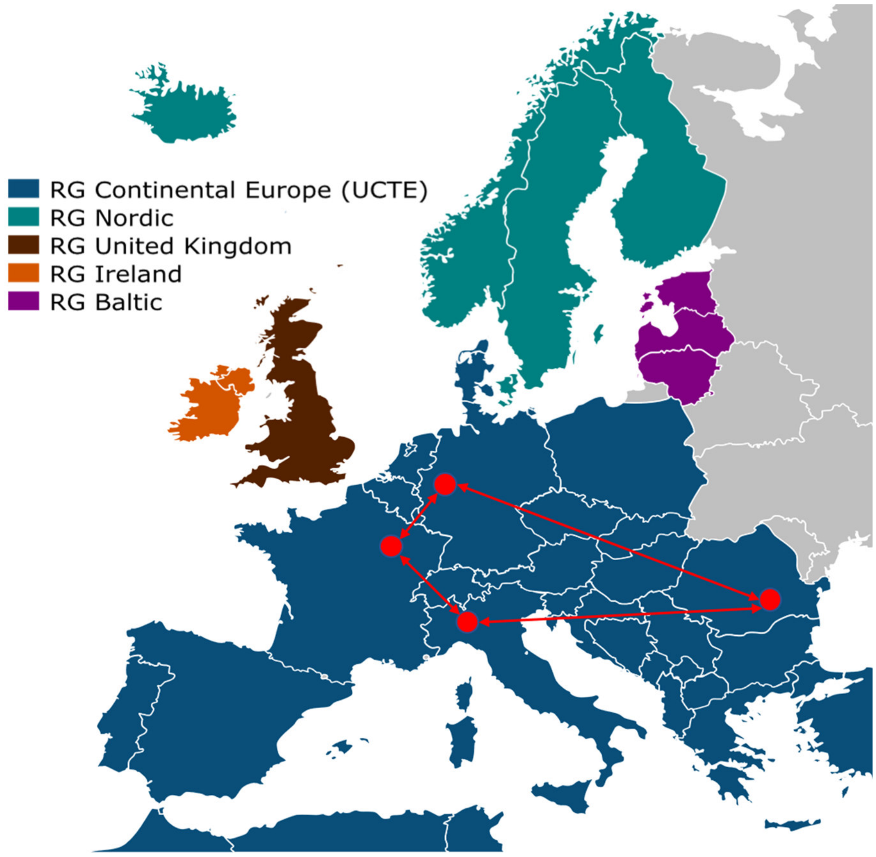

Figure C. 5 PMU measurement points for frequency analysis on January 10th, 2019.

The frequency metered in the points shown in Figure C.5 is illustrated in Figure C.6. A few reference instants, marked to similar shapes, have been drawn by red line. The purpose is:

- To extend the analysis regarding the coupling between power system frequency metered in different countries.
- To verify the synchronization between the low-cost PMUs.

Five reference point has been set to identify whether the frequency values recorded in the six locations match and exhibit the same profile. The conclusion is that the profile matches pretty well, but the intermediary values are not well synchronized. This is because the low-cost PMUs are not capable to providing values on a regular basis because, based on the experience of the authors of this deliverable, loss of data happened quite often. However, the low-cost PMUs can provide acceptable results that allows understanding the behaviour of the Interconnected Network of the Continental Europe.

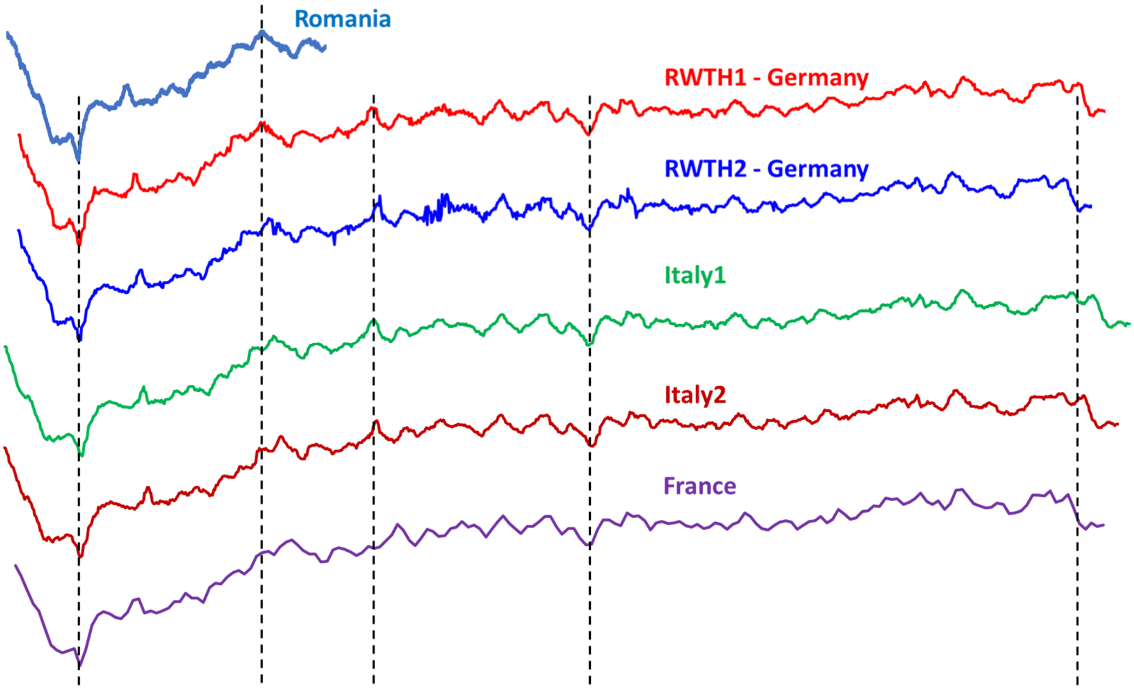

Figure C. 6 Frequency variation on January 10th, 2019, in Germany, Italy, France, and Romania.

Using the available data, besides the causes of the incidents on January 10th, we may conclude the following:

- During slow dynamics, the synchronous machines from the Interconnected Network of the Continental Europe are swinging together. This is seen by the synchronized values of the frequency recorded in different countries.
- Low-cost PMUs can provide data with acceptable accuracy. For better results, a dedicated software that synchronize the data in strings of data with different reporting rate or with missing data is required.
- Developing a Wide Area Monitoring System across Europe is essential for capturing both fast and slow dynamics that helps us analyse and understand the behaviour of the various system dynamics, while pattern recognition may help better identify the origin of the incident. The incidents produce first local frequency variations, while all the other areas remain unaffected, then the frequency is quickly similar in every point.
- Measuring the frequency in the Romanian power system is very important for the analysis because Romania is located at the border of the Interconnected Network of the Continental Europe, and it is expected that the frequency can have a slightly different behaviour in a short term compared to a bus located in the centre of Europe.