RESERVE

D5.4 v1.0

Report on trial for frequency control in Laboratory and validation of initial network codes and ancillary service definitions, V1

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Abstract:

This deliverable provides quantitative and qualitative analysis of the frequency variations in the Romanian power system. Frequency data was collected from different nodes of the Romanian power system. The work focuses mainly on explaining the measurement system set-up, the choice of equipment and of the specific reporting rates enabling system dynamics observation. Additionally, by synchronizing data achieved from different locations, important conclusions have been drawn related to the frequency dynamics in a power system, mainly during propagating events.

Keyword list:

Frequency, synchronized measurements, phasor measurement units, reporting rate, wide are measurement system, data aggregation, statistic analysis.

Executive Summary

This deliverable is the first version of the report on frequency control numerical simulations, and contains qualitative and quantitative information necessary for understanding some aspects of the frequency characteristics and to start preparing the most relevant scenarios for simulations. Therefore, the actual basic technology and architectures employed for frequency control and monitoring are presented. D5.4 is prepared within Task 5.3, **focusing on frequency control**.

Additionally, this deliverable is intended to provide an **overview of the technology deployed for frequency monitoring in power systems**, and the emerging techniques that are expected to replace the actual technology while the renewable energy sources are replacing the classical power plants.

The final goal of the Task 5.3 is to draft relevant network codes recommendations based on frequency simulations performed on the Romanian power system database. In this context, Appendix A explains the basics of the actual **EMS/SCADA architecture** employed for frequency control in Romania, and in particular focussing in the Automatic Generation Control (AGC). The information provided in this chapter helps understanding the purpose of each type of data for frequency control. Deliverables D2.1 and D2.2 present the theory behind the frequency control procedures.

Currently, a large number of **WAMS (wide area measurement systems)** are in operation in power systems around the world aimed at providing information that cannot be obtained with the SCADA system because low reporting rate, low accuracy (the data is updated on a 2 seconds basis), while data collected from different locations is not synchronized. In particular the WAMS in Romania, Italy, and Germany are presented (Appendix B). Additionally, it is important to mention the WAMS coordinated from the Laufenburg centre in Switzerland, that collects data from various PMU installed in several power systems across the Continental Europe zone of the ENTSO-E system. This WAMS in Laufenburg is very important for the future monitoring of the power system dynamics occurring, including frequency, voltage angle and power oscillations. We expect that with the increased share of RES in Europe, long distance power exchanges will be usual options for the provision of electrical energy as well as ancillary services. As the mechanical inertial is decreasing, fast dynamics will be observed all over the system which will further need advanced hardware and software technology for maintaining the power system stability.

Theoretical considerations are presented together with measurement data from different points in the Romanian national grid, as shown in Annex C. The highlights of this study are: the analysis of the effect of the heterogeneous reporting rates on the measurement accuracy, sources of the **communication latency**, 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 are presented. The analysis of the frequency data performed within Task 5.3 is intended to identify, by using high **reporting rate measurements**, the **frequency dynamics** that may occur in the power system. It is expected that these dynamics are more difficult to handle with the actual technology, because frequency will experience faster and deeper variations, as shown in deliverable D2.2.

The observations and recommendations resulting from deliverables D5.4 and D5.5 are classified into three categories:

- Techniques for frequency measurement and data processing;
- New network codes specifications required with the increased share of RES;
- Directions of approach on ancillary services for Work Package WP6.

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Table of Contents

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 system support 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** focuses on the measurements within the UPB laboratory set-up. Theoretical considerations are 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 are presented. The analysis of the frequency data performed within Task 5.3 is intended to identify, by using high sampling rate measurements, the frequency dynamics that may occur in the power system. It is expected that these dynamics are more difficult to handle with the actual technology, because frequency will experience faster and deeper variations, as shown in deliverables D2.1 and D2.2.
- **Deliverable D5.5** will provide conclusions on the use of high reporting rate synchronized measurements on wide area as enabler of RES participation in the frequency control operation. The various simulations of the frequency control performed on the Romanian power system database, defined within WP2, will extensively employ data collected from all 14 PMU measurement points installed in the Romanian transmission network. Power flow data, frequency data and voltage angle data are required to achieve a 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 variations of generation from RES and large unbalances caused by disconnection of generation sources following severe short-circuits.

1.2 Objectives of the Work Report in this Deliverable

The work report in this deliverable aims at:

- Providing the background of the general frequency control architecture in the Romanian power system (RPS), as the frequency control simulations are performed on the RPS database;
- Providing insights on the technology of the future for frequency data acquisition and event visualization, focussing on the Wide Area Measurement systems;
- Providing detailed aspects of the PMU set-ups for frequency measurement, data transmission, and data archiving;
- Investigating the frequency data, from qualitative and quantitative point of view. From qualitative point of view, both the influence of the sampling rate and the electrical position of the measurement point on the resolution of frequency variation are analysed. From quantitative point of view, the amount of data, that impacts the required hardware characteristics, is also investigated;
- Providing outline of the second deliverable for frequency control simulations;

1.3 Outline of the Deliverable

The deliverable details the research efforts in the first year on identifying the actual technology (EMS/SCADA) employed in the frequency control, as well as the emerging technology (PMU) expected to be extensively deployed in order to allow the power system operator to capture the fast dynamics occurring in the power systems in terms of frequency (and, in some cases, power) variations. The challenge is that the technology employed for transferring and archiving, as well as data integration into control software, of the frequency data metered by PMUs is not standardized. For this reason, research activities have been conducted to emphasize frequency particularities, that otherwise cannot be observed, e.g. the influence of the sampling rate on the frequency and the RoCoF variation, 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 in the preparation for performing frequency control simulations. This document can be read in isolation to other deliverables as it is intended to gather and process frequency data. Figure 1.1 shows the placement of this deliverable (**D5.4**) in the wider context of Task 5.3, within the work package **WP5**, as well as the interlinked work packages of the RESERVE project.

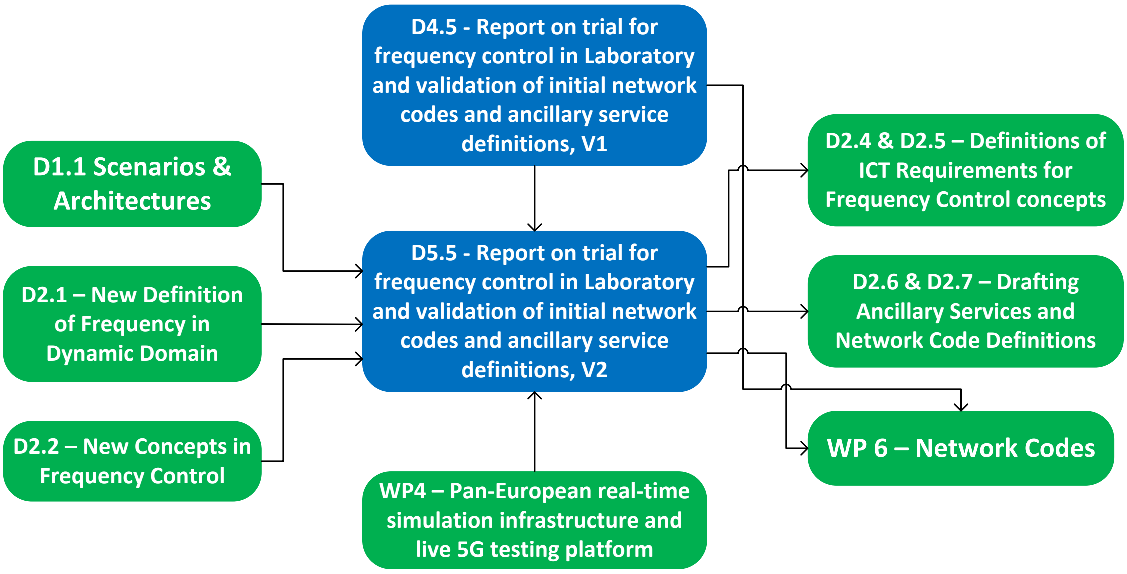

Figure 1.1. Relationships between Deliverables in Task 5.3 and other work packages.

The observations resulted in this deliverable will be used for drafting network codes proposals in Work Package 6. Technical characteristics described in this deliverable are recommended for being used in frequency control simulations that will be done within the work of the deliverable D5.5. The activity for frequency control simulations within deliverable D5.5 are based also on the frequency control techniques developed in deliverable D2.1 and D2.2, and load flow and dynamic models of the Romanian power system provided by Transelectrica, as predated within the Work Package 4.

2. The importance of data measurement for frequency control studies under 100% RES

2.1 The context

The RESERVE project develops new techniques and performs real-time numerical simulations aiming at drafting new or adapted network codes and ancillary services that can enable a stable supply of purely renewable resources, which may include hydro resources, and various typed of inverter-based wind and photovoltaic power plants. The frequency control architecture consists of measuring and estimating the frequency under dynamic conditions and a novel definition of Linearized Swing Dynamics (LSD). To successfully manage energy networks with 100% RES, it is essential that the communications and IT equipment supports the new power grids with fast, reliable, and secure transmission of wide-area field measurements and control commands for managing voltage and frequency in all parts of the network. The analysis of network data of the Irish and Romanian grids have shown to be too complex for being simulated monolithically on commercially available real time simulators. To tackle this challenge the project develops a geographically distributed simulation that solves the inherent communication latencies and integrates the heterogeneous simulation.

2.2 Description of the Romanian power system

The Romanian power system is synchronously interconnected to the ENSTO-E network. Direct interconnection lines operate with Bulgaria, Serbia, Hungary and Ukraine (a small island). Other isolated lines exist with Moldova. Appendix A describes the main characteristics of the Romanian power system, emphasizing the geographical location of the measurement point of interest for frequency monitoring in view of numerical simulations for frequency-based control. The data models that are going to be used within the work to be reported in D5.5 are based on the actual structure that employs the SCADA system in the frequency control architecture, such as:

- Power flows on the interconnection lines;
- Frequency, calculated using the actual standard;
- Total load in Romania;
- Total generation in Romania, and the share of generation from the various resources (coal, gas, nuclear, hydro, wind, photovoltaic, biomass);
- Control Order of the AGC regulator;

Table 2.1 shows the installed power in various generation resources in Romania (July 2017) [39]. This data will be used in projecting the generation mix scenario for 2050, with 100% RES, including also hydo-power. Additionally, the generation and load profiles [38] for different seasons will be taken into consideration in order to estimate the share of generation during different time intervals within a day.

Table 2.1 Current generation mix in Romania [39]

Fuel Type	Number of units	Installed power	Gross Capacity	Net power	Unavailability	Available power
Coal	39	6240.267	5190.267	4467.067	1318	4922.267
Natural Gas	280	5792.887	3941.288	3433.677	2054.2605	3738.6265
Hydro	974	6761.8129	6707.9019	6374.9983	326.6789	6435.134
Nuclear	2	1413	1413	1300	0	1413
Wind	116	3025.954	3025.629	2974.1514	16.37	3009.584
Biomass/Biogas	50	130.253	129.423	120.7472	3.017	127.236
Solar	606	1378.1049	1378.1003	1285.292	69.66824	1308.4367
Geothermal	1	0.05	0	0	0.05	0
Total	2068	24742.329	21785.609	19955.933	3788.0446	20954.284

2.3 Integration of Phasor Measurement Units as a need to control the power systems under 100% RES

2.3.1 On the use of the PMUs

Synchronized measurements have become a common feature in modern electric power systems. The use of accurate time signals (from a satellite system like GPS) allows estimation of voltage and current parameters, including frequency and their phasor representation. One of the first practical outcome is the availability of directly estimation of relative voltage phase angles, of paramount importance in the operation of power systems.

Synchronization can be achieved using two methods:

- The sampling pulses are synchronized to a GPS (Global Positioning System) receiver and samples are taken at the same time in all devices with an error dictated by the ability of the sampling clock to phase lock;
- The samples are time stamped precisely with respect to the GPS receiver time tag followed by the correct processing of the data samples and time tagging of the output data.

The information accurately describing the energy transfer in a power system can be derived: (i) from a set of averaged quantities (like rms values of voltage, currents, active power etc.) assumed to be constant over a defined time interval together with a commonly accepted model for the system under study or (ii) from a set of measurements (phasors) having a common time reference. The first situation corresponds to the classically deployed state estimation, while the second case is best described by the Wide Area Measurement System using PMUs.

A phasor measurement unit (PMU) is a synchronized measurements device, able to offer both magnitude and phase angle. PMUs are used for voltage and current phasor measurements. PMU standards give detailed information on uncertainties associated with phasor measurements. Voltage and current phasors are accurately time-stamped, as PMU is synchronized with a GPS to a common time reference. The maximal uncertainty associated with the local measurement channels is for frequency less than 1 ppm (0.0001%) of reading, plus timebase error while for the time stamp is 1 µs plus timebase error; timebase error is less than 1 µs. The data from all connected PMU's are collected, synchronized and archived by the Phasor Data Concentrator (PDC) function and delivered with minimum latency (in the order of tens of ms) to other client application for display, analysis and control purposes.

It is important to underline that, in both cases, the quality of the model adopted for describing the energy transfer is of paramount importance [36]. For example, frequency, voltage and/or current phasors (amplitude and angle) are simultaneously measured by each PMU, and information is delivered grace to a synchronization with the GPS time reference (1.0 µs or better accuracy).

It is also important to use a similar model for designing the control process as the one embedded into the measurement system delivering input data for the control algorithm. For example, the paradigm of unique frequency in an interconnected system, for steady state operation, can be challenged based on PMU measurements. Appendix C shows this variability of frequency and rate of change of frequency, when PMUs in four different nodes of the Romanian power system are used with the maximal reporting rate (50 frames per second).

To address non-steady state situations, the PMU approach is more suitable for measuring the frequency, as it can deliver frequency values at programmable reporting rates of 10, 20 or 40 milliseconds (for 50 Hz main frequency), giving the possibility for aggregations made outside the measurement unit.

In figure B.7 it has been shown that in non-steady state situations the frequency delivered by PMUs is not the same in the whole system and that at the place of an incident the frequency variation is higher than at a certain grid distance. In fact, as the system is not in steady-state, the traditional way of defining frequency need to be changed for short-term measurements (e.g. 10 to 40 milliseconds).

A reporting rate in between the low reporting rate of 10 seconds for frequency, defined in [17] and high reporting rate down to 10 milliseconds, specific to PMU, is obtained with some smart meters types, which are able to give new values each one second, with a resolution of 10 mHz. This is particularly interesting because it allows that smart meters properly used [23] can provide frequency measurements which may be used in automating DER behaviour if reaction time is e.g. of max 2 seconds (maximum admissible initial delay t_1), as it is requested in frequency sensitive mode ('FSM') in [24] for type C power generating modules with inertia or for LFSM-O implementation for type A and B generating modules stipulated in the same code. Table C.2 from section C.4.2 shows the different frequency reporting characteristics, for PMUs and smart meters.

One may consider adding to the actual trend, in addition to the classical primary *f-P* control implemented through the frequency sensitive mode ('FSM') [24] which demands for a maximum initial delay of 2 seconds and maximum full activation time of 30 seconds, new regulations for quicker reaction in power regulation based on frequency. The example is the Enhanced Frequency response (EFR) requested by National Grid (UK) for 201 MW of capacity [34] in addition to the Firm Frequency Response (FFR), having total response under 10 seconds.

Additional services to provide synthetic inertia in power systems with reduced mechanical inertia will RoCoF calculation in short intervals such as each 40 milliseconds, in order to be able to simulate natural inertia.

2.3.2 Aspects related to the RoCoF measurements

In this context, the model for energy transfer conventionally adopted by PMU deployment is described in IEEE C37.118.1-2011 Standard [33], which defines synchrophasors (Note: shorten name for synchronized phasors), frequency, and rate of change of frequency (also called rate of change of frequency – RoCoF, rocof or ROCOF) measurement under all operating conditions. It specifies methods for evaluating these measurements and requirements for compliance with the standard under both steady-state and dynamic conditions. This standard is based on the experience of the PMU manufacturers and defines the actual technics for calculating RoCoF. However, no appropriate standardization for RoCoF testing exists. Presently there is an IEC group (**CENELEC/TC8X/WG7, on frequency and ROCOF measurement requirements**) working on definitions for frequency and rate of change of frequency with relevance to power system measurements.

In [35] it is emphasized that a way to quantify the frequency deviation is by computing its rate of change (rate of change of frequency, rocof), also for steady-state network operation. However, presently there is no agreement on how this information shall be obtained and what should be the optimal reporting rate. Moreover, one can note that the "system particularities" in terms of local dynamics are recognized in the ENTSOE Network Codes [8] where the rate of change of frequency is mentioned as one of the input quantities for loss of mains (LoM) relay settings: "the facilitation of a Demand Facility or Closed Distribution Network to voluntarily deliver Demand Side Response Very Fast Active Power Control by a change of Active Power related to the RoCoF for that portion of its demand, shall be agreed between the Relevant TSO and Demand Facility Owner or operator of a Closed Distribution Network, in coordination with the Relevant Network Operator, while respecting the provisions of Article 9(3)". Table I synthesizes similar requirements proposed by the European Norm [9].

Table 2.1. RoCoF requirements as of [9] in European Countries

Country	Trip value LoM (RoCoF) [Hz/s]	Trip delay setting time (maximal value) [s]
Cyprus	0.6	0.5
Denmark	2.5	0.2
UK	0.2	1
Ireland	0.4	0.5
Latvia	0.4	0.5
Finland	>2	5
Slovenia	Not required	Not required

For other European Countries, the RoCoF is not mentioned in [9]. Moreover, in [10] the only mention of the rate of change of frequency is “2.117: frequency relay device that functions on a predetermined value of frequency - either under or over normal system frequency or rate of change of frequency”.

The only references to RoCoF are made in the control and protection areas. However the primary information is given by frequency measurement, which is done in the IEC 61000-4-30 [40] framework only. This standard silently assumes a model for the energy transfer with high inertia, i.e. voltage and current waveforms have slow variation (time constant in the order of hundreds of milliseconds). The model uses a formalization of data compression, i.e. the use of rms values for describing quantities with (quasi-)sinusoidal variation which is mapping all samples of a periodical quantity over analysis widow into a single point *X*, its rms value.

Recalling that measurement process is always a goal-driven process and that the measurement result is meaningful only when the quality of the measurement process is quantified [41], it becomes essential to estimate the contribution of the measurement context (described by it conventionally adopted model) to the overall uncertainty:

$$u = \sqrt{u_M^2 + u_E^2}$$

where u_E is the standard uncertainty of the measurement equipment and u_M is the standard uncertainty which describes the model approximation.

For example, the IEC 61000-4-30 standard includes a data compression module by indicating an algorithm for time aggregation of information on frequency (and voltage, current, distortion factors etc). Appendix C shows the filtering effect of deploying such algorithms to PMU information made available with high time granularity (according to the selected reporting rate) which finally degrade the overall measurement quality due to large u_M, although the component u_E is diminished by successive averages.

2.3.3 The need for harmonization in developing WAMS

There is no specific standard regarding integration of PMUs into a WAMS. All WAMS developed around the word are proprietary systems, which means that they have been designed at the suggestion of a company that intends to promote its patents.

In this deliverable we have provided some details related to the **Wide Area Monitoring Systems (WAMS)** implemented by Transelectrica, and the laboratory set-up at UPB, that integrates PMUs installed in the distribution network buses. Brief description of the WAMS developed in Italy and Germany are also presented (Annex B).

Currently, a large number of WAMS are in operation in power systems around the world aimed at providing information that cannot be obtained with the SCADA system because the data is updated on a 2 seconds basis, while data collected from different locations is not synchronized. It is important to mention the WAMS created at the Laufenburg centre in Switzerland, that collects data from various PMU installed in several power systems across the Continental Europe of the ENTSO-E system. This WAMS in Laufenburg is very important for the future monitoring of the power system dynamics, including frequency, voltage angle and power oscillations. We expect that with the increased share of RES in Europe, long distance power exchanges will be usual options for provision of electrical energy as well as ancillary services. The mechanical inertia in the power systems is decreasing as a consequence of replacing the classical power plants with the power electronic based units. As a consequence, fast dynamics consisting in fast and deep frequency fluctuations will occur. Such behaviours need careful study by using advanced hardware and software technology.

2.4 Recommendations for network codes and ancillary services

Based on the initial work done within Task 5.3, the following proposals for further approach are emphasized:

- Procedures for time-aligning (and resampling) of **synchronized information from measurement units characterized by different sampling rates**;

- **New frequency definition** is necessary in fully agreement to the model adopted for the control purposes. The frequency data analysis has shown that even today, in transient conditions, the frequency measured at different busses are different. However, the measurements are pursued with 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 sampling rate** for necessary for calculating the RoCoF, under the same condition of adopting a non-ambiguous definition of frequency and rate for change of frequency quantities.

3. Proposed procedure of the frequency control simulations

In Appendix C we have identified some qualitative and quantitative analysis useful in preparing the data for frequency control simulations. Depending on the type of dynamics that we want to analyse, two simulation environments will be employed: the real-time simulator and the Eurostag software.

Figure 3.1 illustrates the basic scheme of the simulations that will be performed on the Romanian power system database. The Romanian power system is interconnected with the power systems from Bulgaria, Serbia, Hungary, as well as with an island of the power system from Ukraine. The input data are the load flow database and the dynamic data of the Romanian power system, the power flow on the interconnection lines, and measured data by Transelectrica of significant events.

When testing the interconnected laboratories, that include the real-time simulators from RWTH and Polito, we will proceed as shown in Figure 3.1. For the purpose of simulating interconnected power systems, the file containing the power flows on the interconnection lines, recorded on a time window of interest for a specific event, will be uploaded on the computers from Polito, WIT and UPB. The data will be then read by means of the VILLASnode software hosted by RWTH.

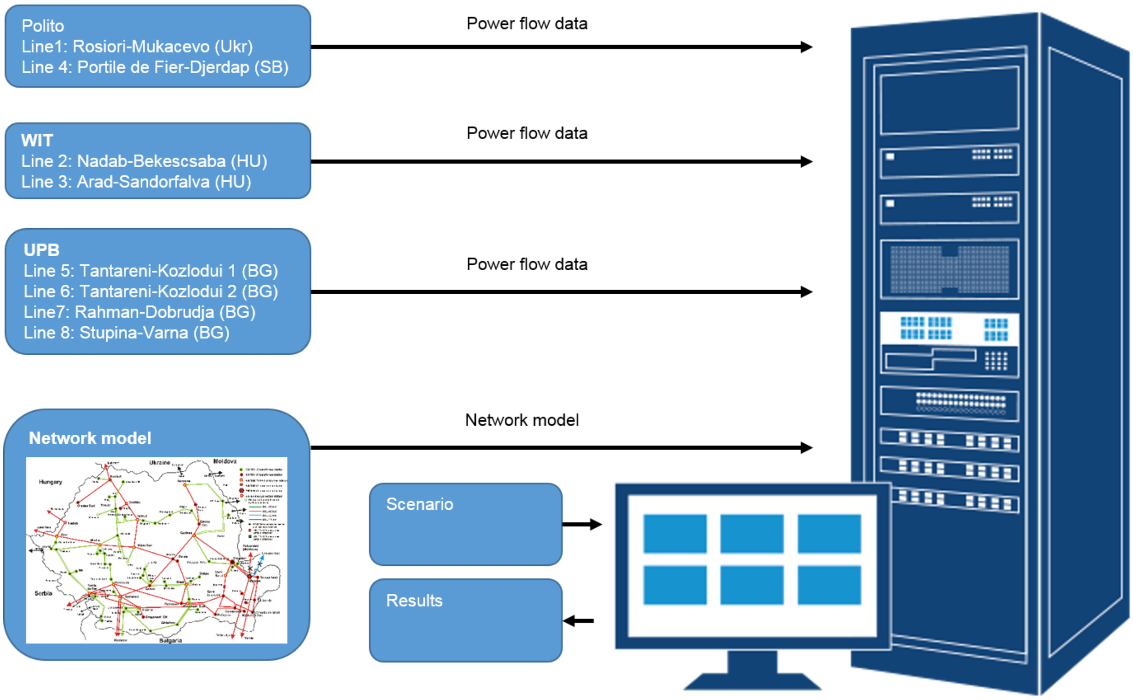

Figure 3.1. The basic concept for simulating the frequency control on the interconnected laboratories real-time system.

Other simulations will be performed by UPB in the Eurostag software to test some dynamic model on the extended model of the Romanian power system, as well as the operation of a virtual power plant or a microgrid when intended to be used for frequency control.

4. Conclusions

The electrical power systems and undergoing significant changes in terms of monitoring and control. These are underlined as follows:

- The actual SCADA technology become obsolete because its reporting rate of 2 seconds cannot capture the fast dynamics that are anticipated to happen in the power systems in the context of increasing the share of generation from RES up to 100%. Therefore, new technology and systems are necessary. The PMU (phasor measurement units) devices have been extensively tested in various pilot projects, while WAMS (wide area measurement systems) have been developed. However, this equipment cannot be considered fully reliable at this time because of the uncertainties originating from the lack of testing standards.
- An European wide area measurement system (WAMS) is about to be developed in the Continental Europe. It collects data from various PMUs located in few power systems. The plan is to develop it by integrating PMU from all ENTSO-E power system located on the Continental Europe. Currently, this system is used for monitoring purposes only. In order to extend its capability, wide area control and protection functions should be implemented. This is required in order to take appropriate actions in the case of large occurrence of phase angle variations, that will characterize the power systems in the context of 100% RES. Such capabilities will, of course, need elaborating new network codes for operation, involving the collaboration between the TSOs.
- The PMUs and similar equipment is used today for collecting data with high granularity to allow capturing the fast dynamics of the power system frequency. Three types of metering equipment have been used in our work for collecting the data, and they prove that the most advanced one is capable of meeting the future needs of the power systems.
- Using real-data measurements we have observed that the frequency is not the same in all the power system nodes. This indicates that the presence of the branch impedances makes the generation units not to be perfectly synchronized. This comment is today done in the context of safely big mechanical inertia ensured by the thermal power plants. It is expected that in the future, while the mechanical inertia is decreasing and fast dynamics will occur, the differences between the frequencies in the different nodes of a power system will be significantly big. Therefore, it will be more and more difficult to ensure the power system stability it appropriate measures will not be taken.
- Some techniques have been used within the work of this deliverable for processing the frequency and rate-of-change-of-frequency data collected from the PMUs available in the UPB laboratory. We have focused on analysing data during important perturbations that occurred in the Romanian power system. In the next phases of this project we will collect data during each event, for which we will have information about the causes and the severity in terms of power unbalances. All the data collected will help us to identify the correct correlation between the severity of the event and the frequency variation. This will help us to appropriately define the scenarios for frequency simulations that will be done within the work of the deliverable D5.5.

All these observations will be further used for drafting the final proposals for network codes or standards.

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6. List of Abbreviations

AGC	Automatic Generation Control
aFRR	automatic Frequency Restoration Reserve
B2B	Business to Business
BMS	Building management system
CAPEX	CAPital EXpenditure
CDF	Cumulative Distribution Factor
CENELEC	European Committee for Electro technical Standardization
CEP	Complex Event Processing
COTS	Commercial off-the-shelf
CPMS	Charge Point Management System
CSA	Cloud Security Alliance
EMS	Decentralised energy management system
DB	Database
DER	Distributed Energy Resources
DMS	Distribution Management System
DMTF	Distributed Management Taskforce
DSE	Domain Specific Enabler
DSO	Distribution System Operator
EAC	Exploitation Activities Coordinator
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
ERP	Enterprise Resource Planning
ESB	Electricity Supply Board
ESCO	Energy Service Companies
ESO	European Standardisation Organisations
ETP	European Technology Platform
ETSI	European Telecommunications Standards Institute
GE	Generic Enabler
GPS	Geographic Positioning System
GUI	Guide User Interface
HMI	Human Machine Interface
HV	High Voltage
I2ND	Interfaces to the Network and Devices
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
IP	Internet Protocol
KPI	Key Performance Indicator
LV	Low Voltage
M2M	Machine to Machine
MPLS	Multiprotocol Label Switching
MV	Medium Voltage
NIST	National Institute of Standards and Technology
O&M	Operations and maintenance
OPEX	OPerational EXpenditure
PDC	Power Data Concentrator
PM	Project Manager
PMT	Project Management Team
PMU	Phasor Measurement System
PPP	Public Private Partnership
PSA	Power System Analysis
RSA	Rivest–Shamir–Adleman
RTU	Remote Terminal Unit
QEG	Quality Evaluation Group
S3C	Service Capacity; Capability; Connectivity
SCADA	Supervisory Control and Data Acquisition
SDH	Synchronous Digital Hierarchy
SDN	Software defined Networks

SDOs	Standards Development Organisations
SET	Strategic Energy Technology
SET	Strategic Energy Technology
SG-CG	Smart Grid Coordination Group
SGSG	Smart Grid Stakeholders Group
SME	Small & Medium Enterprise
SMX	Smart Meter eXtension
SO	System Operator
SoA	State of the Art
SS	Secondary Substation
TCP	Transmission Control Protocol
TL	Task Leader
TLS	Transport Layer Security
TM	Technical Manager
TO	Transmission Owner
TSO	Transmission and System Operator
UDP	Used Datagram Protocol
UPB	University Politehnica of Bucharest
USM	Unbundle Smart Meter
VPN	Virtual Private Network
VPP	Virtual Power Plant
WAM	Wide Area Measurement system
WP	Work Package
WPL	Work Package Leader

Annex A. Current hardware architectures employed for frequency control

A.1 The EMS/SCADA architecture in Romania

The Romanian Power Grid Company "Transelectrica" S.A. (Transelectrica) is the owner, operator and administrator of the transmission system is Romania. In 2004 it became member of ENTSO-E (European Network of Transmission System Operators for Electricity), which at that time was called UCTE. The major responsibilities of the company are:

- Transmission network operation
  - Maintenance, operation and upgrade of the national high-voltage electric backbone;
  - Operation of cross-border interconnection lines;
  - High availability (low outage) rates;
  - Unrestricted grid access for users;
- Dispatching and system services
  - Real time monitoring of the whole electricity system in Romania;
  - Grid balance planning i.e. a close match between generation and consumption;
  - Calculation of the requirement for back-up stand-by generation;
- Balancing market operation
  - Grid balancing: measurement and settlement of grid imbalances caused by temporary generation-consumption mismatch situations (acting as clearing agent for the entire market).

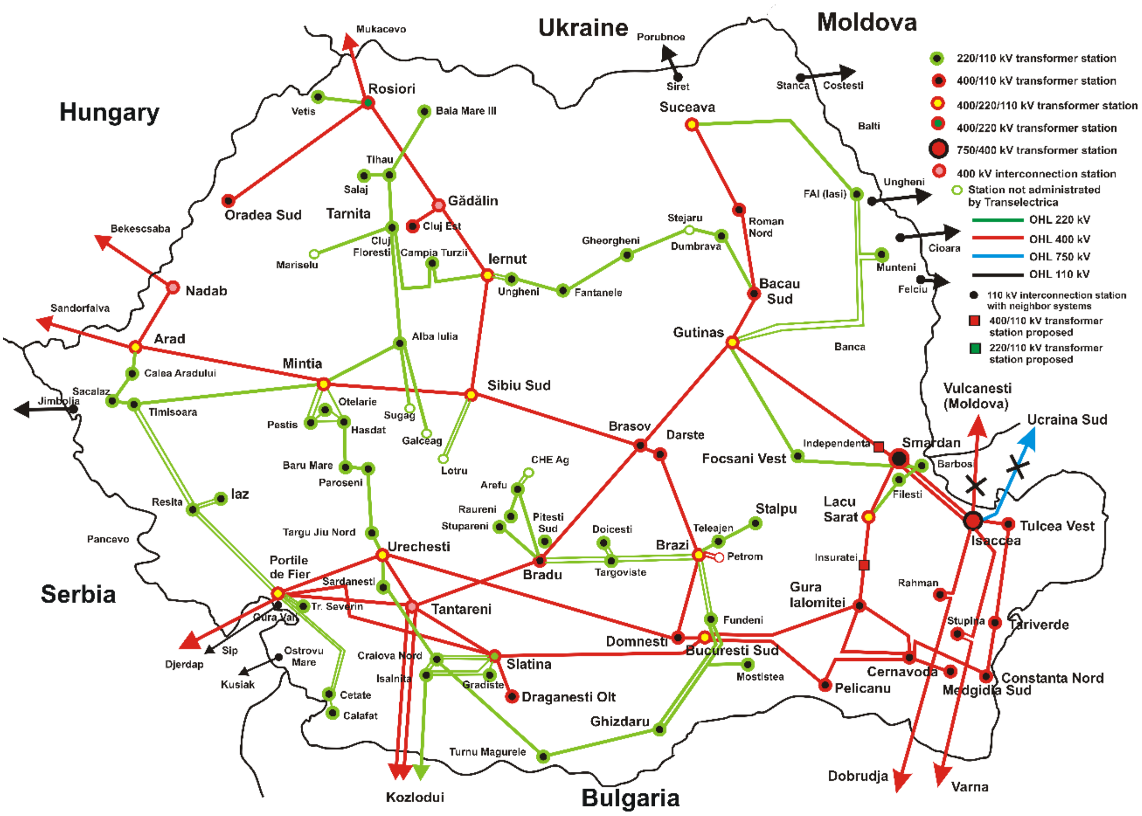


Figure A.1. Single-line diagram of the Romanian Transmission Network [38].

Transelectrica is the only operator providing the services of electricity transmission, operational technical management of the Romanian Power System (RPS) and electricity market administration (by means of its subsidiary OPCOM SA). Such a domain is considered to be a natural monopoly under the law. In Romania, the energy area is subject to regulations issued by the Romanian Energy Regulatory Authority (ANRE). The legislation consists of both Energy Law and secondary legislation, which are in full agreement with the Transmission and System

Operator (TSO) License, Electric Transmission Network Code, Commercial Code, and the Metering Code 0.

The company was founded in year 2000, when the vertically integrated utility CONEL (National Electricity Company) was privatized and separated into several network and generation companies. Most of the 110 kV grid has been transferred to the distribution companies, except for a few lines that are stability constrained transmission corridors. Therefore, Transelectrica has under its jurisdiction only the 220 kV and 400 kV electrical networks. A diagram of the Romanian transmission system (RTS) is shown in Figure 1. The RTS is interconnected with the power systems of Moldova, Ukraine, Hungary, Serbia and Bulgaria.

The Romanian transmission system consists of:

- 81 substations, including one 750 kV substation, 38 substations at 400 kV, and 42 substations at 220 kV, as well as approximately 216 transformers with a total installed power of 38,058 MVA;
- 8,834.4 km of transmission lines encompassing 3 km of 750 kV lines, 4912 km of 400 kV lines, 3875.6 km of 220 kV lines, and 40.4 km of 110 kV lines, if which 486.2 km of interconnection lines.

The supervision of System operation is realized by a centralized SCADA/EMS system, which plays two major roles: (1) it is responsible for the real-time acquisition and processing of all data pertaining to the operation of the RPS, and (2) it provides the monitoring of operation and remote control of approximately 350 generators and 660 substations under the operational jurisdiction of the National Dispatch Centre (NDC) and five Territorial Dispatch Centres (TDC). National Dispatch Centre (also called UnO-DEN in Romanian) is the administrative entity that monitors, supervises, and controls the power system. There are five Territorial Dispatch Centres are located in Bucharest, Timisoara, Craiova Bacau and Cluj. The Bucharest Dispatch Centre (BDC) is located in the same building as the NDC.

The hierarchical SCADA/EMS structure is shows in Figure A.2. All servers and all communication paths are doubled in order to ensure redundancy. The BDC was designed as a mirror of the NDC. Double direct communication exists between the four remote TDCs and the two dispatch centres in Bucharest. The SCADA/EMS is configured in such a way to provide system operation from any of the five TDCs.

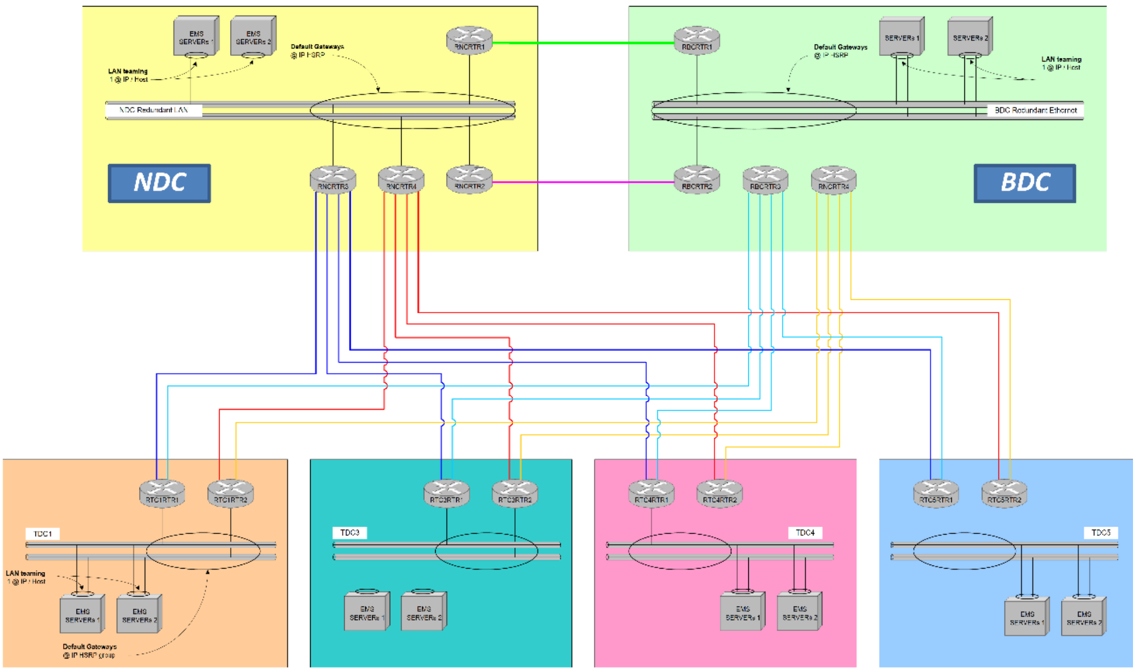


Figure A.2. Hierarchical SCADA/EMS structure.

The Romanian TSO has developed an intensive process of upgrading most of the transmission substations, including the secondary circuits, and a large number of different types of protection and control systems were put into service at the transmission substations level. Simultaneously, along the 400 kV and 220 kV overhead transmission lines owned by Transelectrica, a fibre optic (FO) backbone was deployed. This means more than 5000 km of FO cables, using OPGW and OPUG cables and related equipment such as DWDM (Dense Wavelength Division Multiplexing) and SDH (Synchronous Digital Hierarchy), both with the synchronizing system, and the management platforms.

A simplified hardware architecture of the National Dispatching Centre is shown in Figure A.3. The components that are directly involved in frequency control are the SCADA/EMS Servers, the Front-End Servers, and the GPS Time & Frequency unit.

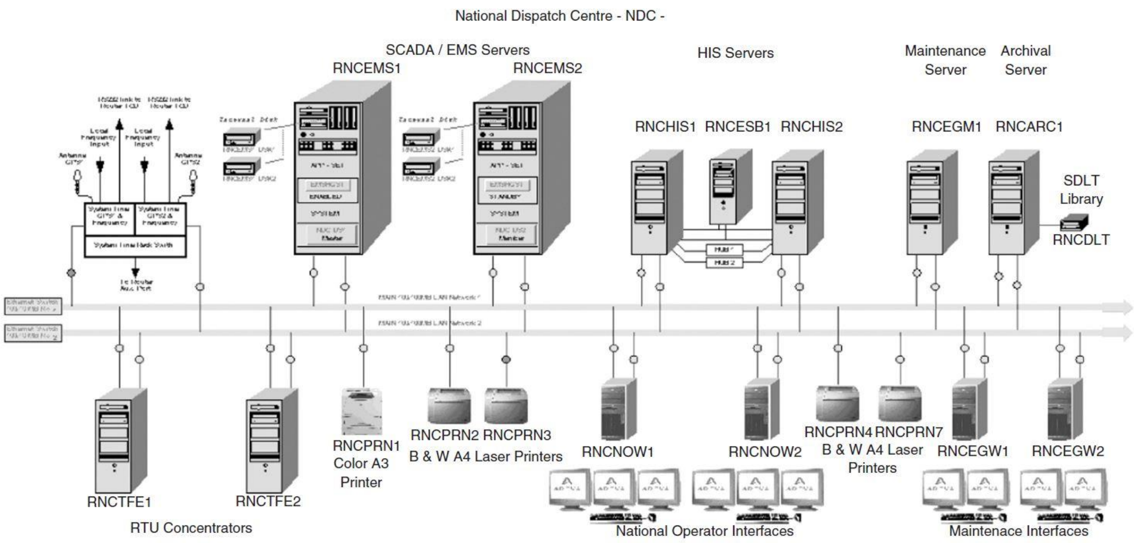


Figure A.3. SCADA/EMS configuration at the National Dispatch Centre.

Figure A.4 shows the applications implemented into the NDC's EMS. In consists of three types of applications assigned to three databases. Each application uses its own database, which allows it to run and store instances of relevant data. The applications highlighted in red are related to the secondary frequency control.

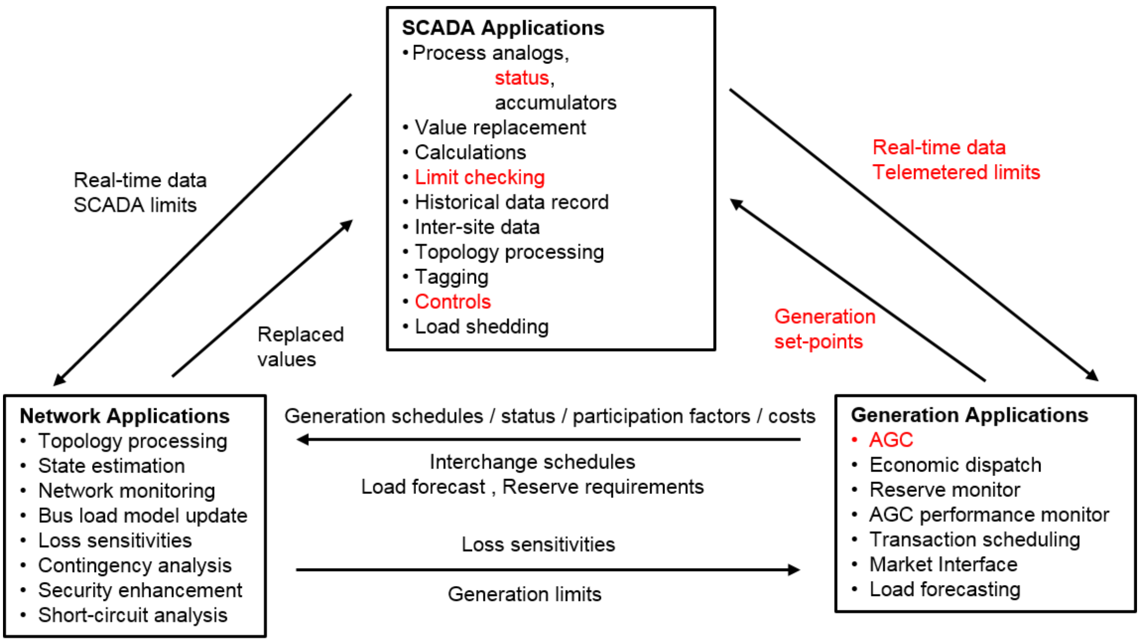


Figure A.4. SCADA/EMS applications implemented at NDC.

For example, the AGC application is a component of the Generation Application. Its input data are provided by the SCADA database. It calculates the required set-points for power generators for achieving optimal energy flow, by minimizing the Area Control Error (ACE). The newly derived set-points are updated into the SCADA database, from where they are sent to control the generation units.

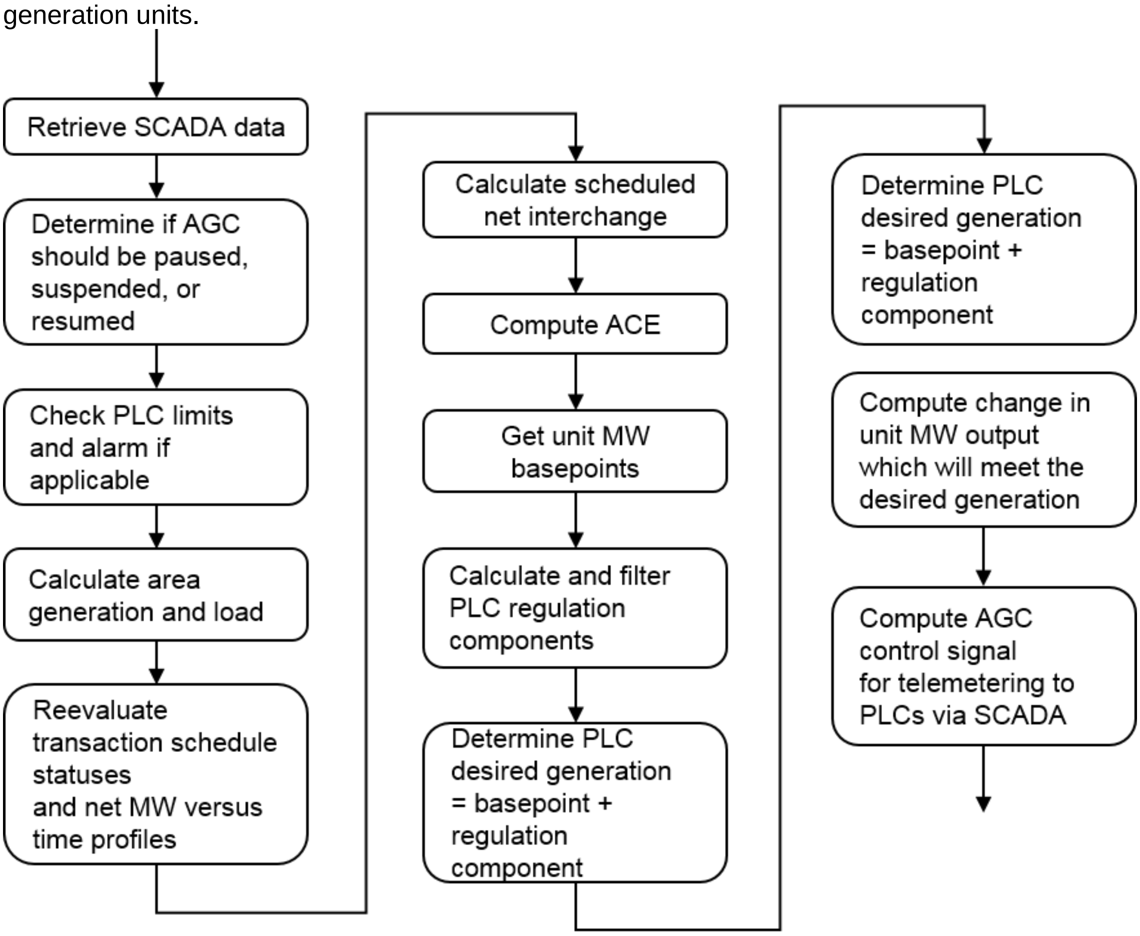
A.2 The Automatic Generation Control application

The core of the secondary frequency control is the Automatic Generation Control (AGC) application implemented within the EMS[1]. The input data to AGC are:

- Network operation information:
  - power flows on the interconnection lines;
  - frequency, as estimated from high accuracy measurement units (PMUs).
- Generators' information (assigned to the AGC):
  - status (on/off);
  - available power band;
  - P/Q constraints.
- Generators' models:
  - Static limits: min, max
  - Dynamic limits: ramp rates

Using this information, AGC calculates:
- New generation set-points for the control generation units (power plants).

The basic chart-flow of the AGC implemented at the Romanian NDC's EMS is shown in Figure A.5. In includes all steps taken by the AGC to determine the new set-points for the control generation units.



[1] EMS (Energy Management System): A supervisory (computer) system, gathering (acquiring) data on the process and sending commands (control) to the process.

Figure A.5. AGC execution steps.

Data describing the power flow on the interconnection lines is collected by means of the RTUs[2] installed in substations on the Romanian side of each line. All data is sent to the national dispatching centre, and are stored into the SCADA database. Figure A.6 shows the simplified connection between the RTUs and the NDC, together with the corresponding variable.

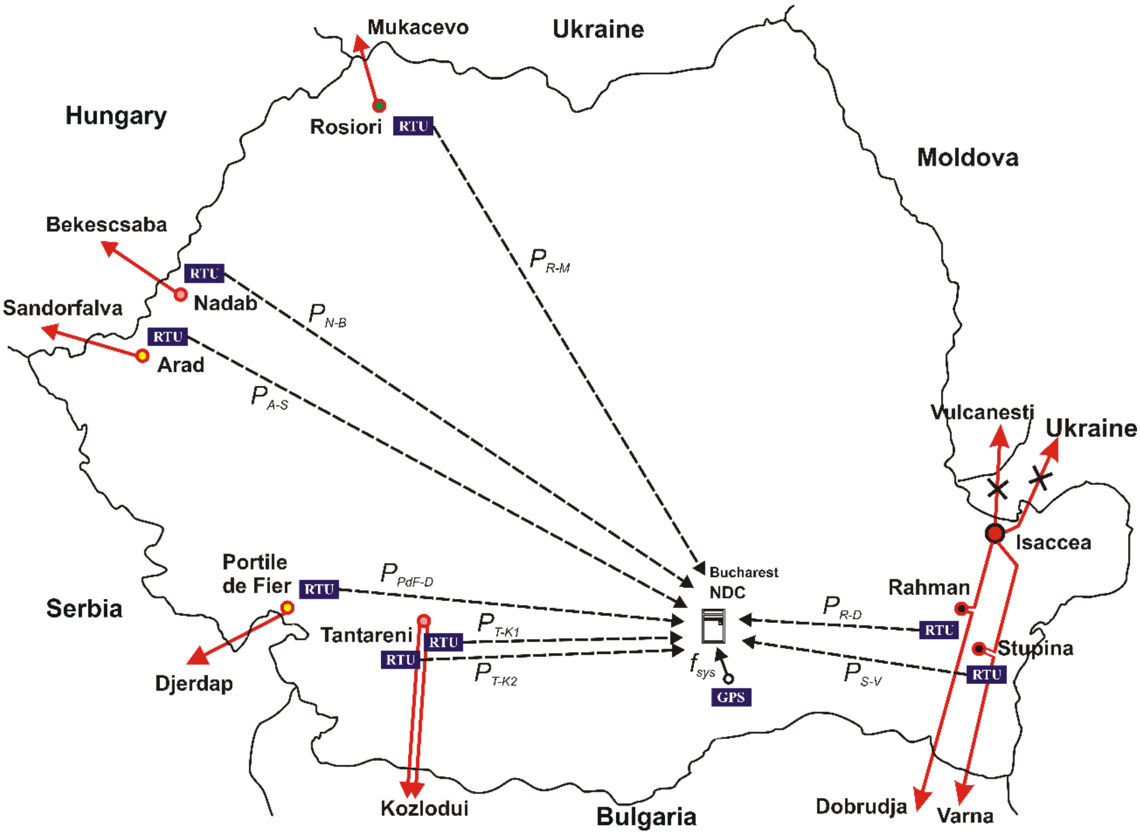


Figure A.6. Data acquisition by SCADA for AGC.

The power flow variables are also presented in Table 1.

Table A.1. Variables measured for AGC calculations.

Substation	Interconnection line	Measurement	Neighbour country
Nadab	Nadab-Bekescsaba	P_{N-B}	Hungary
Arad	Arad-Sandorfalva	P_{A-S}	
Portile de Fier 1	Portile de Fier 1-Djerdap	P_{PdF-D}	Serbia
Tantareni	Tantareni-Kozlodui 1	P_{T-K1}	Bulgaria
Tantareni	Tantareni-Kozlodui 2	P_{T-K2}	
Rahman	Rahman-Dobrudja	P_{R-D}	
Stupina	Stupina-Varna	P_{S-V}	
Rosiori	Rosiori-Mukacevo	P_{R-M}	Ukraine

Besides the information acquired from the network data and the generator data, AGC receives information from Market server, that is the basepoint at generation unit[3] level (MBP) and regulation band at generation unit level (MRB). Additionally, it may take into account the generator characteristics (models).

[2] **Remote Terminal Units** (RTUs) connect sensors in the process, convert sensor output signals to digital data, and send digital data to the supervisory system.

[3] A **generation unit** is an electrical power plant that can consist of several generators.

A generic representation of the relationship between the AGC application database and other databases is depicted in Figure A.7.

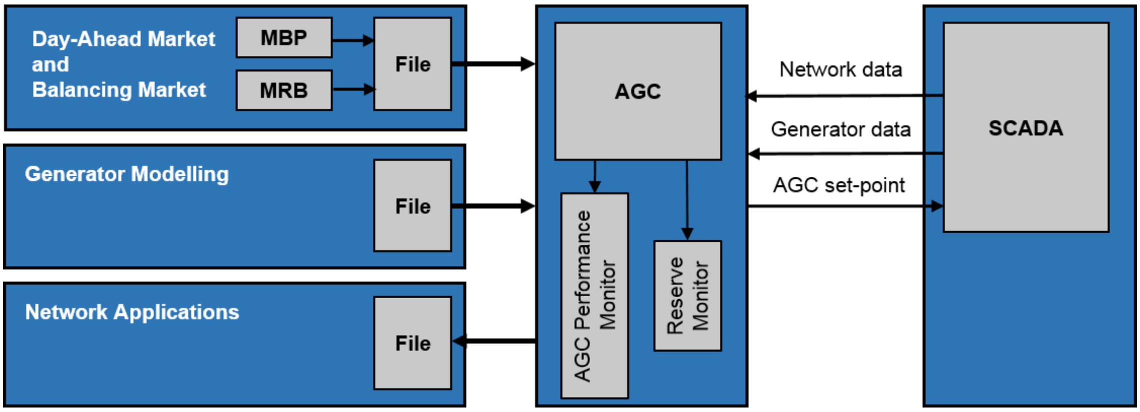
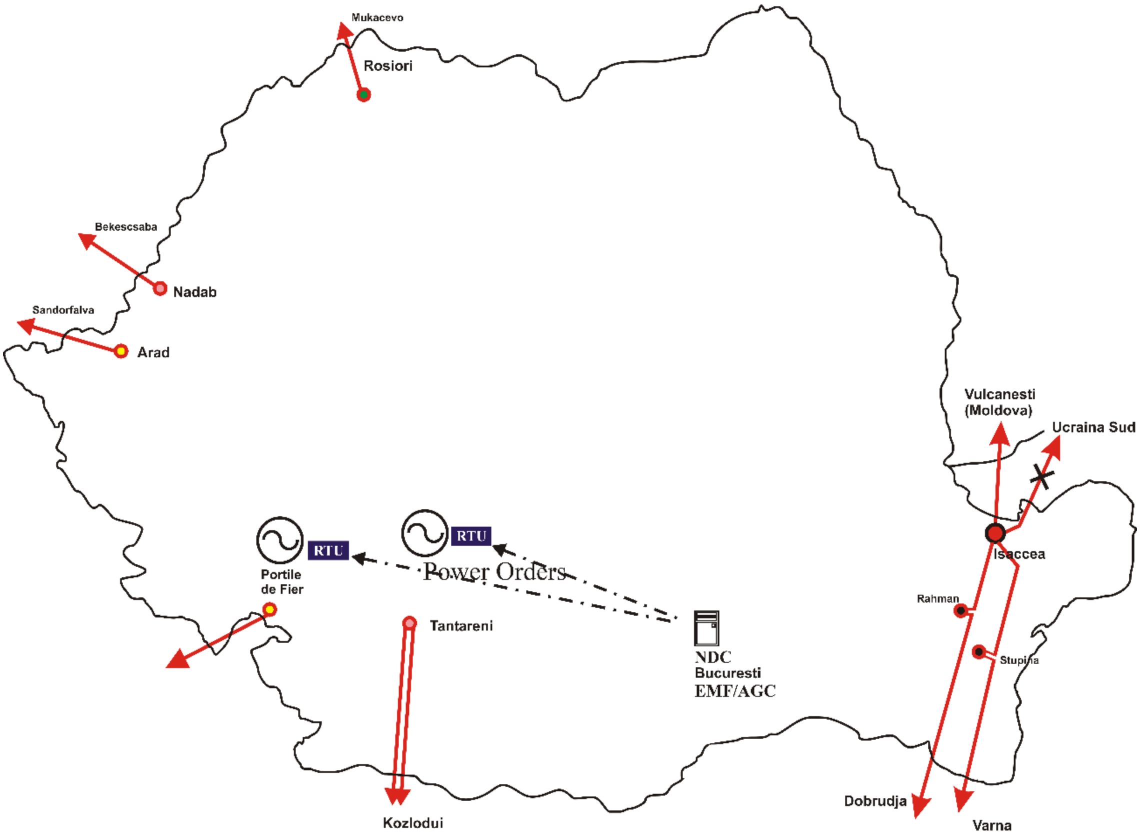


Figure A.7. Connection of the AGC application to various databases or applications.

The power set-points calculated by the AGC application are sent to each participating generation unit via SCADA communication infrastructure. The communication is ensured through the glass-fibre infrastructure administrated by Teletrans[4]. At the generation unit level, the signal received from the AGC application is then assigned to each generator based on a predefined strategy, momentary technical aspects.

Currently in the Romanian power system, the number of power plants that are regularly employed to provide automatic frequency restoration reserve is reduced. This is because there are a few hydraulic power plants that have specific technical characteristics and can provide a FRR. Figure A.8 illustrates an example of the returned signal from the AGC to the regulating generation units.



[4] **Teletrans** is the company that provides telecommunication, IT and process information / SCADA infrastructure to Transelectrica, as well as to several public and private clients. Teletrans shares are 100% owned by Transelectrica.

Figure A.8. Illustration of control order send by AGC to the generation units.

At the generator level, control units based on Programmable Logic Controllers (PLCs)[5] are used to control the operation. The PLCs combine all available signals that form the output power set-point of the generator. These signals consist of: generator load order, primary frequency control order, secondary frequency control order, and tertiary frequency control order.

[5] A programmable logic controller, PLC, or programmable controller is a digital computer used for automation of typically industrial electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or light fixtures (Wiki)

Annex B. Wide area measurement systems (WAMS)

B.1 Wide Area Measurements in the Romanian power system

In Romania, the Wide Area Measurement System (WAMS) consists of fourteen phasor measurement units (PMUs) connected to the buses of most important power system substations, and a central server. The current circuits of the PMUs are connected on the interconnection lines, and in substations close to very large generating units. On interconnection lines, there are 8 PMUs installed at Rosiori, Nadab, Arad, Portile de Fier I, Tantareani, Rahman, Stupina, and Isaccea. The other 6 PMUs are installed in the following substations: Mintia, Iernut, Gutinas, Brasov, Bucuresti Sud and Cernavoda [1].

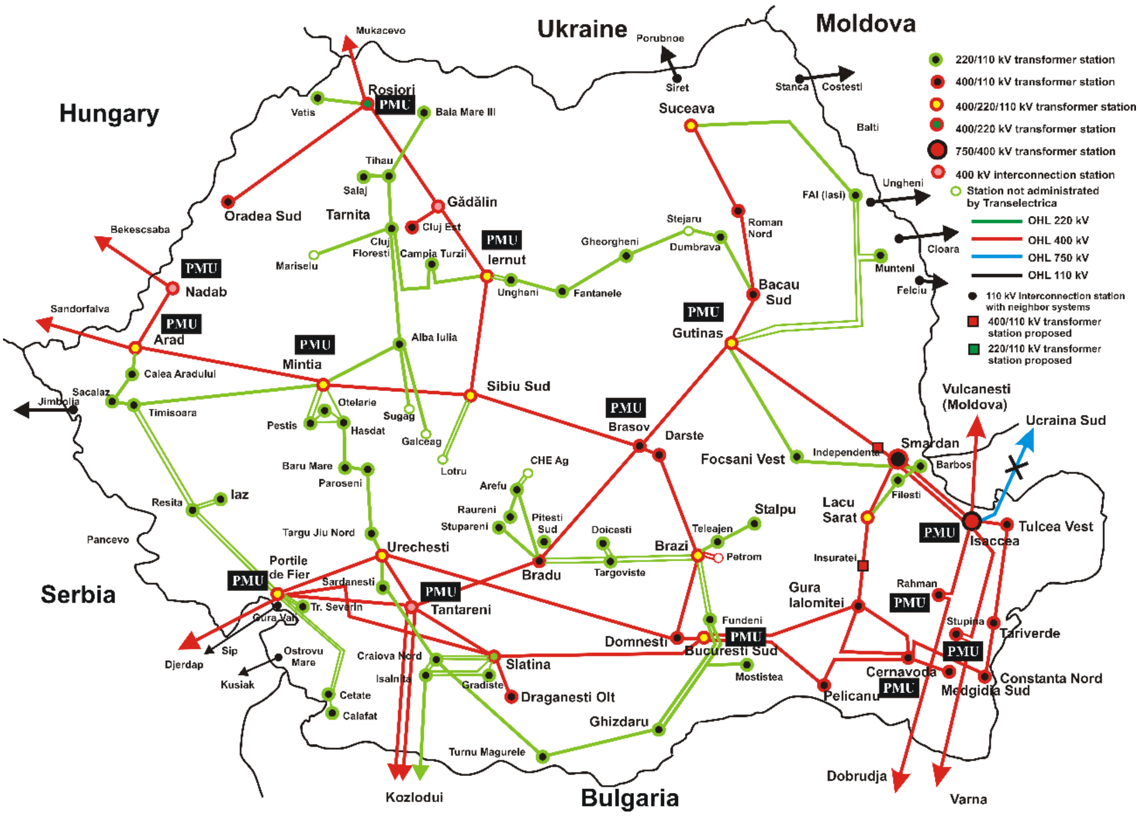


Figure B.1. PMU locations in Romania [2].

The architecture of the WAMS in Romania is shown in Figure B.2. It includes the PMU locations and the architecture of the central system.

The *local deployments in* each measurement point, is identical. It consists of the PMU device (SEL-451), a Satellite Synchronized Clock (SEL 2407) and a Power Data Concentrator (SEL 3373). The data frame delivered by each PMU (which requires the time signal from the satellite synchronized clock) is sent to the corresponding PDC. The communication is ensured by the Ethernet Switch (SEL 2725) and a fibre optic media converter (LAN/WAN).

The *architecture of the central system* is based on the Central Synchrophasor[6] Processor (CSP). It collects data reported by the 14 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 C37.118-2005 standard, i.e. 30/25 frames per second).

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

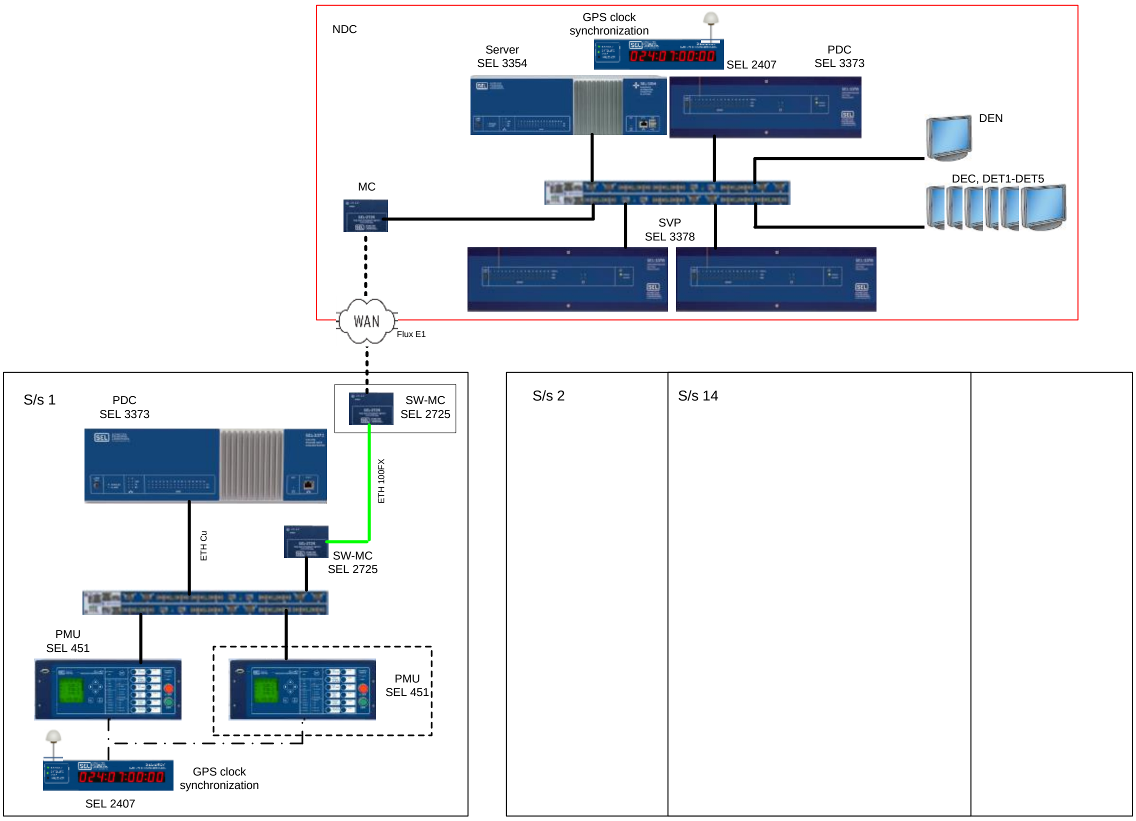


Figure B.2. Hardware architecture of the WAMS in Romania.

The data analysed by the Central Synchrophasor Processor can be displayed using real-time visualization software either at the National Dispatch Centre, or at one of the five Territorial Dispatch Centres.

The Central Software which is used for real-time visualization for detecting and solving some power system challenges is based on SEL-5078. This software package offers: automatically detection of transients due to RES-based, power electronics controlled, electricity generation; power system insight beyond SCADA capabilities, with a high time granularity of 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 [4], [5]. 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.

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 B.3.

Polar coordinates		Rectangular coordinates	
VALPMM	VALPMA	VALPMR	VALPMI
VBLPMM	VBLPMA	VBLPMR	VBLPMI
VCLPMM	VCLPMA	VCLPMR	VCLPMI

Figure B.3. Example of data format of the synchrophasor measurement.

Figure B.4 illustrates the exchange of data from the 14 measurement points and the central power data concentrator. The aim of the PMUs installed on the interconnection lines is to provide power flow data (similar to those provided in Table A.1). Voltage magnitude, frequency and voltage angles are also reported.

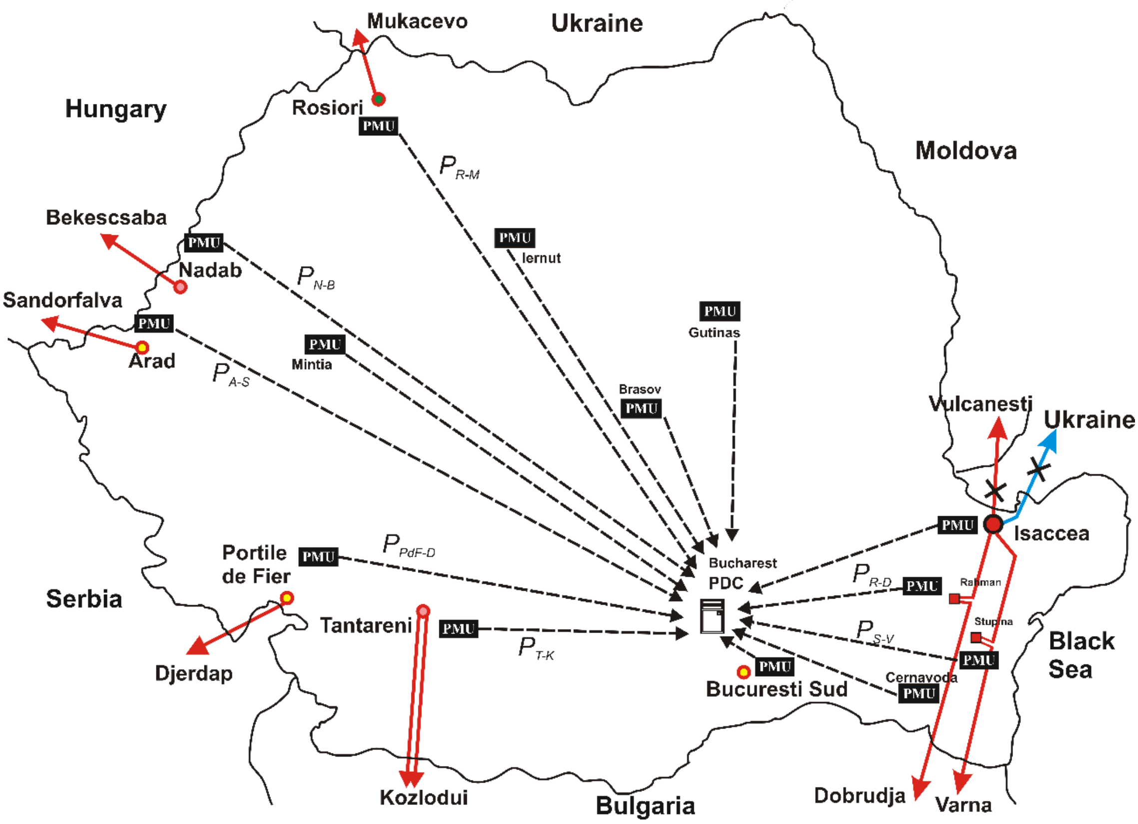


Figure B.4. Illustration of data collection in the Romanian transmission network.

The WAM system implemented in the Romanian power system includes a software dedicated to both real time monitoring and post-event analysis. Figure B.5 illustrates the graphical user interface (GUI) for monitoring the angle differences between different voltage phasors. A higher phase angle difference is observed between the voltage phasor at Cernavoda and the voltage phasor at Rosiori. A colour based representation is used to better emphasize the phase angle differences and by such the system operation.

Figure B.5 shows the GUI for visualization of the main steady state quantities, such as frequency, voltage magnitude, voltage angle, active power and reactive power. If necessary, for post-event analysis purposes, the voltage and current magnitudes on each of the three phases can also be displayed.

The power flows on the interconnection lines can be also displayed, while the relative power flow variation can provide a qualitative understanding of the direction of emergency aid. This is important from the perspective of introducing a balancing market component for trading the frequency containment reserve.

A 24 seconds time window containing the frequency variation for an anonymized event that occurred in the interconnected power system of ENTSO-E is shown in Figure B.6. It is important to note that, the all frequency values come from the PMUs installed in the transmission network, where the impedances are smaller, relative to the voltage level and allow a better electrical coupling (synchronization) between network busses. As also observed in Figure B.7, during transient events, the frequency at the various network busses is different.

The data collected from the PMUs installed in the Romanian power system will be subsequently used within the activity for elaboration of Deliverable 5.5, in connection with Work Package 2, to perform dynamic numerical simulations for testing various theories related to the benefits of the PMU measurements in the case of fast dynamics, focusing on the inertial control and primary frequency control.

Figure B.5. Monitoring the phase angle difference in the Romanian transmission system by existing WAMS.

Figure B.6. Monitoring the network parameters in the Romanian transmission system by existing WAMS.

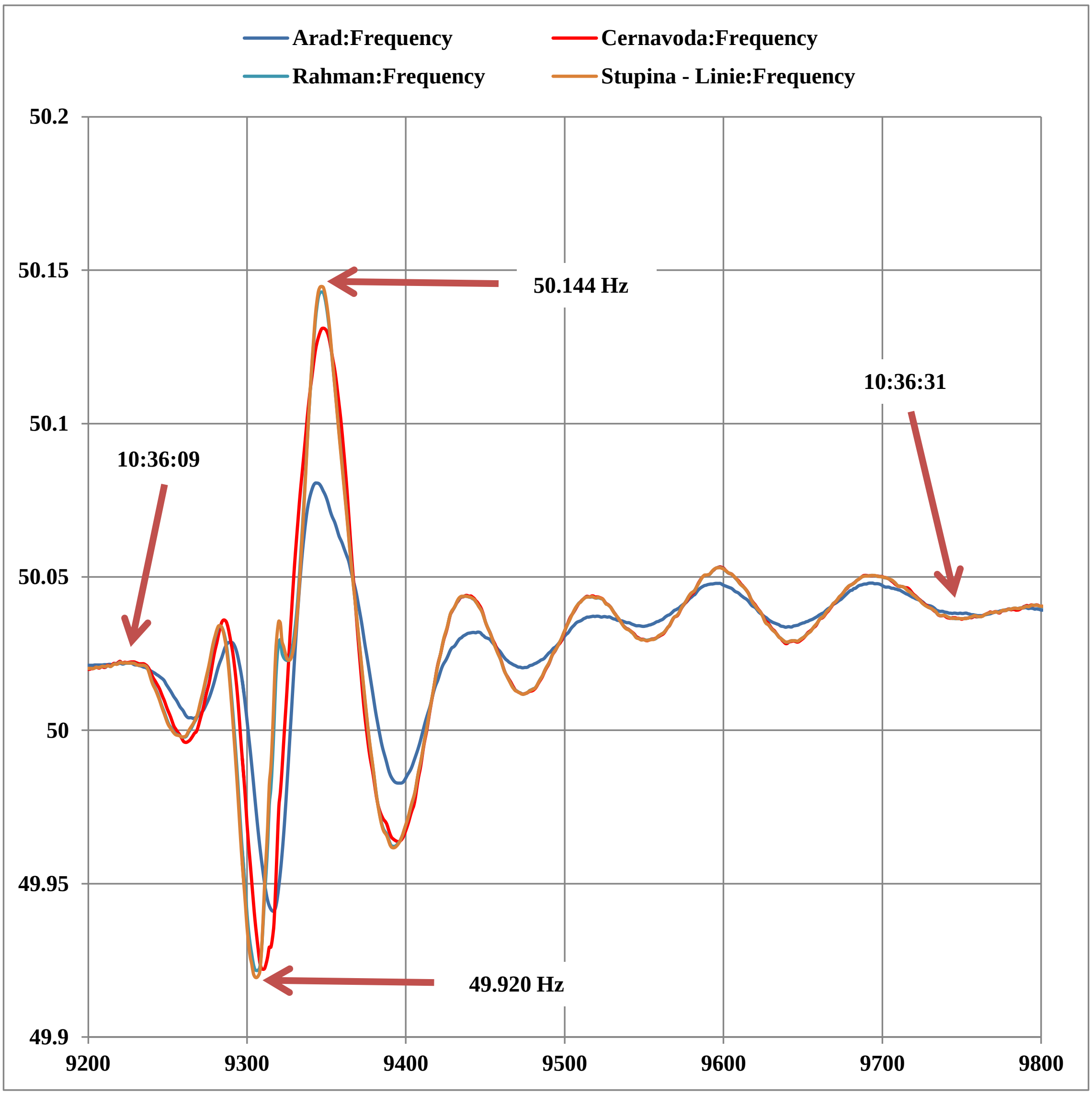


Figure B.7. Frequency variation recorded with the WAM system implemented by Transelectrica.

B.2 UPB laboratory set-up

B.2.1 Technical characteristics of the measurement equipment

B.2.1.1 PMU technical characteristics

Arbiter 1133A

One of the PMUs own by UPB is the Arbiter 1133A. The Model 1133A measures system [7] (absolute) phase angle, system frequency deviation, and system time deviation. Phasor measurement data in accordance with IEEE Standard 1344, at a rate of 20 per second, is standard. This data allows for sophisticated, real-time monitoring and control of stability and power flow. These measurements are made possible with the Model 1133A's internal GPS synchronization.

A built-in Global Positioning System (GPS) satellite receiver synchronizes your Model 1133A within 1 µs of Coordinated Universal Time (UTC), which may also be converted to your local time. With synchronization, revenue data can be accumulated in intervals as short as one minute. Other substation equipment, such as digital fault recorders, solid-state relays, remote terminal units, and programmable logic controllers, may be synchronized with the standard IRIG-B unmodulated time code output.

The accuracy of measurements is ensured by the PMU-related standards. One can select the reporting rate as to provide data matching the high time granularity to the numerical simulation environments in the RE-SERVE project. For example, WAMS in Transelectrica is set to 25 frames/s, which is not enough to fully characterize transient phenomena.

Table B.1. PMU's technical characteristics.

Input	**Configuration**	3ø: 3-element, 2½-element, 2-element, selectable 1ø: 2-element, 1½-element, and 1-element, selectable
	Voltage	Range: (3ø/1ø) 0 to 69, 120, 240, or 480 V, selectable (phase-to-phase for 2 elements; phase-to-neutral for 2½ and 3 element) Over range: 88, 175, 350 or 700 V, nominal
	Current	Range: (3ø/1ø) 2.5, 5, 10, or 20 A, selectable, per element Over range: 2.9, 5.9, 11.7, or 23.5 A, nominal (maximum continuous input current: 20 A per element, all ranges)
	VA, W, VAR	Range: Product of rated voltage and current ranges and number of elements (2½ (3ø) and 1½ (1ø) element, use 3 and 1, respectively)
	Frequency	Range: 45 to 65 Hz, for specified accuracy Harmonics: To 3 kHz
Interface	**Communications**	Serial: Port 1 RS-232 (1133opt10), RS-422/485 half-duplex (1133opt11), Modem (V.34bis, 33.6k) (1133opt12) Port 2 RS-232 (1133opt20), RS-422/485 half-duplex (1133opt21), Modem (V.34bis, 33.6k) (1133opt22) Ethernet: One, 10Base-T per IEEE 802.3i
	Protocols	• Proprietary: PowerSentinelCSV (PSCSV) • Standard: DNP 3.0, MODBUS, PQ-DIF, IEEE C37.118
Specifications	**Accuracy**	• active power and energy: 0.025% of reading, 10% of range or greater and PF > 0.2; 0.005% of apparent power for PF < 0.2 • Under range 0.0025% of range, below 10% of range • apparent power, apparent energy: Same as active power and active energy except no PF effect • reactive power and energy: Same as active power and energy: except replace PF with (1 – PF2)0.5 • voltage magnitude (rms): 0.02% of reading or 0.002% range, whichever is greater

		• current magnitude (rms): 0.03% of reading or 0.003% range, whichever is greater • voltage, harmonics: 0.04% of reading or 0.004% range, whichever is greater • current, harmonics: 0.06% of reading or 0.006% range, whichever is greater • Phase Angle, ø: 0.01°, phase-to-phase or voltage-to current, 10% of range minimum • Power Factor: 0.0002•sin(ø), 10% of range min. • Harmonics: 0.05% THD or 5% of reading, whichever is greater • Frequency: < 1 ppm (0.0001%) of reading, 50 or 60 Hz nominal, plus timebase error • System Phase: 0.03° plus [timebase error • 360° • frequency] • System Time: 1 µs plus timebase error • Event Inputs: ±10 µs (typical)
System Control and Monitoring	**System Time, Phase and Frequency**	• System Time: Unlimited accumulation with ±1 µs resolution • Frequency: 7 digits, xx.xxxxx Hz • System Phase: 0 to 360° with 0.01° resolution • Effect of DC & Harmonics filtering: None; Rejected by narrow-band digital
	Phasors	• Standard: Per IEEE 1344, IEEE C37.118 [7], or PSCSV • Rate, selectable: 1,2,5,10,25,50/sec (for 50 Hz). Including frequency and df/dt.
Synchronization	**General**	• Tracking: GPS–L1, C/A code (1575.42 MHz); 12 channel (tracks up to 12 satellites) • Acquisition: 2 minutes typical • Accuracy: UTC-USNO ±1 µs (only need 1 satellite with correct position) • Out-of-Lock Indication: Via system interface and status display; optional, via contact closure
	Synchronization Output	Type: One; IRIG-B000 or IRIG-B003 per IEEE Std. 1344 (unmodulated or level-shift), 200 mA peak; pluggable 5 mm terminal strip with mating connector, two-pole
	Timebase Error	• GPS locked: Less than 1 µs, when locked to at least one satellite with correct position

		• Unlocked: 10 ppm, typical, after being locked for 10 minutes minimum (<1 second/day unlocked, typical)
Certifications and Approvals		• Compliance to IEC-687 International Standard for AC Static Watthour Meter for Active Energy • Compliance to IEEE C37.118 Standard for Synchrophasors for Power Systems • Certificate of Conformance to NIST CE mark/label and certification

microPMU [9]

In order to acquire information on the power system events in dynamic situations, the reporting rate and pre-processing of measurements are of crucial importance. PMUs are using minimal pre-processing of acquired signal, and it is in form of information concentrators (phasor estimation from voltage and current waveforms on a time window of 2…5 fundamental periods).In this stage, the information is filtered only by the selection of the energy transfer model, i.e. symmetrical (and is eof direct component) and quasi-state sinusoidal and periodical waveform (phasor definition). An additional term of the information transfer without losses is the data compression stage represented by the user selection of the reporting rate. To improve the quality of data and to emphasize the importance of higher sampling rate of frequency values for fast dynamics analysis, specific to the inertial control, UPB has acquired and integrated brand-new PMU technology, including one microPMU which is a power quality analyser from the PQube family manufactured by PowerStandardLabs [9] with synchronization capabilities. The main characteristic that differentiates the microPMU is that this is the first measurement device fully compliant with IEC 61000-4-30 ed3.0 [17], including the steady-state assessment.

Its main characteristics are as follows [9]:

- Ultra-accurate phasor measurements! **0,001° resolution** on voltage and current phase angles, **2 PPM resolution** on voltage and current magnitudes;
- Fast recording and reporting rate: 2 times per cycle (100 frames/s at 50 Hz);
- 3 voltage and 3 current angle-magnitude pairs;
- Frequency, fundamental total apparent, active, reactive and power factor;
- Ultra-accurate time stamping thanks to patent-pending calibrated GPS antenna/receiver (fully electrically isolated for safety – cable length delay compensated;
- Phasor data streaming according to C37.118-2011, rate up to 100/120 frames/s. Fully compatible with OpenPDC, the standard phasor data concentrator software.
- Measurement data recorded in (16GB) internal memory for 14 days – tolerates complete loss of communication channel with no loss of research data;
- Recordings can be downloaded via FTP, embedded Web server (HTTP) for configuration modification, firmware update;
- Tiny footprint. Can be snapped into electrical panels, distribution poles, pad-mount transformer;
- Direct connection to any world-wide power grid voltage: 50/60 Hz, 100V ~ 690V, single-phase or three-phase;
- Fully supports PT’s (up to 100 kV) and CT’s;
- Powers from POE (power over Ethernet), 24-48VDC, 24VAC, or 110VAC/230VAC with a plug-in module, optional 30min or up to 3hour backup power modules available.

The technical characteristics of the microPMU, useful for voltage and current measurement, as follows:

MAINS VOLTAGE INPUT CHANNELS

Frequency Range	Nominal 50 Hz, 60 Hz.
Mains Configuration	Single-phase, split-single-phase, delta, wye/star. User selected or auto-selected.
Range of Nominal Input Voltage	100 V ~ 960 V L-L (69 V ~ 480 V L-N). User selected or auto-selected.
Measurement Channels	Line-to-Earth, Neutral-to-Earth
Sampling Rate	25600 samples/s @ 50Hz
Measurement Range	0 V ~ 750V L-N (0 V ~ 1300 V L-L)
TVE (Total Vector Error)	**Typical TVE ±0,01%**
	Typical short-term TVE stability for differential measurements: ±0.002%
Amplitude resolution	0,0002% FS (2 PPM) (noise floor – useful for short-term difference measurements)
Amplitude Accuracy	±0,050% (10V - 750V L-N). Typical : ±0,010% (120V - 600V L-N)
Angle resolution	0.001°- (noise floor - useful for short-term difference measurements)
Angle Accuracy	±0,010° 1 Standard Deviation Typical: ±0,003°

CURRENT INPUT CHANNELS

CT Input Ratio Range	1:1 to 50000:1
Nominal Input	0.333 V (rms)
Input Impedance	33.3kΩ
Crest Factor	3.5 (±1.17 Vpk)
Sampling Rate	Same rate as mains voltage measuring channels

Unbundle Smart Meter (USM) technical characteristics

The SCADA system has been developed with synchronization capabilities, which allows coping with milliseconds timeframe for addressing the event-driven time-stamps; however, the measurements further used in control algorithms (not protection) such as: active and reactive power, currents and voltages (rms values), or frequency, are not subject of a standardized algorithm, in what concerns both the reporting rate and the aggregation procedure.

The so-called internal reporting rate is usually not synchronized with the internal clock (used for other SCADA enabled services). Reporting rates of 1 or 2 measurements per second for SCADA can be reached by some Remote Terminal Units (RTU) / Bay Control Units (BCU) or Intelligent Electronic Devices (IED). However, reporting rates on the whole chain between e.g. a substation and a control centre can be in the range of several seconds (2 to 5 seconds). At the control centre level, we can rely on a generic 3s reporting time intervals between data frames arriving from different network measurement nodes.

Smart meters provide useful information on the energy transfer with reporting rates in the range of minutes (usually 15 minutes). However, most of them are capable to deliver information on a second-base, limitations consisting mostly in the communication channel bandwidth and data storage capabilities of the metering operator. A solution has been recently proposed: the Unbundled Smart Meter (USM), which is adds to existing metrology meters features which extend the information availability.

Several USMs [26, 27], designed within the Nobel Grid European project [30], have been installed at University Politehnica of Bucharest. The USM can be externally synchronized at the level of 1 second, usually by means of meter specific protocols (e.g. DLMS). Although the internally computation of energy values can use real-time measurements with sampling rates in the order of several (rms) values per second, the accessible reporting time for external readout of such real-time (instrumentation) values is usually in the range of 1 to 5 seconds. The full chain readout of such data by a control centre with metering front-end may have similar time uncertainty for the synchronization of received measurements.

The USM consists of compatible modules of different functionalities, which may be added or removed any time. The modules are thus integrated in an unbundled configuration, and the meter is called *Unbundled Smart Meter* (USM). The proposed USM architecture [30] is presented in Figure B.8 and consists of the following two main components [29]:

a) *Smart Metrology Meter* (SMM), provided with mandatory metrology features and functionality, dealing also with hard real-time functionalities. The stored data cannot be deleted in any other way than through buffer recirculation after e.g. 6 months or 2 years (some of it being legally relevant). This component is like the classical (digital) electricity meter.
b) *Smart Meter eXtension* (SMX), which has high flexibility to accommodate new functionalities that support smart grid operation, provision of various energy services by either supplier or the customer, multi-user management, or multi-protocol communication with various actors directly involved in electricity supply service to the end-user.

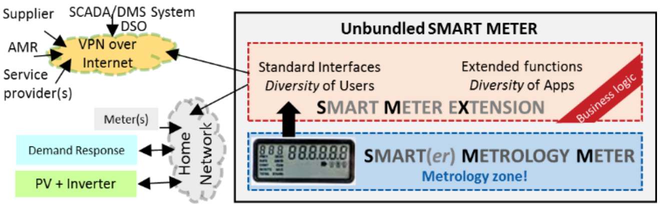


Figure B.8. Unbundled Smart Meter architecture [30].

USM is a complex equipment that can serve various actors in many ways. It can become an Internet oriented Smart Meter (IoSM) by integrating IoT features in the SMX module. Compared with the already classical Smart Meters, which may have IP connection for remote browsing and parameterization, an IoSM needs to cope specifically with high requirements of cyber-security as well as privacy and multi-user approach. Some non-exhaustive requirements of an IoSM that can serve multi-actors, including Smart City and end-user, are summarizing as follows:

- Accessibility through IP address (IPV4/6) with visibility over internet, e.g. through Virtual Private Network (VPN) endpoint, through direct access as server for services or connected to an Internet Protocol (IP) server to provide its services;
- Secure communication using strong encryption and authentication, based on Key Management Infrastructure (KMI) policies tailored for large deployments;
- Multi-user functionality, by accepting many simultaneous connections, e.g. the distribution system operator – DSO), the electricity service supplier, Smart City/community, ESCOs, end-user;
- Multi-protocol, e.g. Device Language Message Specification (DLMS) for billing, IEC61850 for SCADA in smart grids, publish-subscribe solutions for ESCOs;
- Mitigation of at least three main roles in the IoSM's SMX part (which is also the gateway to internet, with potential vulnerability by default): the Smart Meter operator, which can be usually the DSO; the prosumer/end-customer, which is the legal owner of the meter data; and the Smart City authority. This should be done in a hierarchical structure using new technologies to allow the legal access and operation of the meter;
- Privacy by design, which allows the data to be exchanged with authorized external agents only; a Role-based Access Control (RBAC), employed to provide specific access to various actors, is mandatory needed;

- IoSM features, to act as a gateway, with firewall functionality between the Smart Grid and the Smart Home IoT, to support delivery of energy related services.
- Intrusion detection, malware encapsulation and firewalling;
- Audit activity based logs of events and other specific actions.

While the last two features are general IT recipes applied in all systems, the first seven features are a result of both IT specific recipes and Smart Meters/Smart Grid specific requirements.

B.2.1.2 Communication infrastructure modules

The communication infrastructure used for the set-ups presented in this deliverable has many components like the Timetools equipment used to determine the communication delays, reprogrammed internet routers and 3G modems from different telecom ISPs.

Timetools LC2750 [10]

TimeTools new LC2750 RS232 Serial GPS timing receiver provides computers and computer networks with a highly precise timing reference. The LC2750 provides a reliable, highly accurate, traceable, source of time inside your firewall.

Timing information to +/-60 nanoseconds can be provided via a RS232 serial interface. Typically, an 800MHz Pentium PC running Linux can be synchronized to within 1 microsecond of UTC.

The characteristics of the devices are:

INPUT \ OUTPUT	• GPS Antenna Input TNC female • AUX Output: 9 way ‘D’ RS232 output • Power: Double Fused IEC Inlet
INTEGRAL GPS RECEIVER	• Type: 12 Channel, L1 1575.42 MHz • Timing: GPS Time Traceable to UTC (USNO) • Accuracy (typical): +/- 60 nsec UTC • Acquisition (Cold Start): 38 sec

Internet connection

Long range data transfer is possible using internet routers and GSM data plans from different providers. In the UPB laboratory most of the applications use one type of wireless router with a customized firmware. The characteristics of this router and of the modems used are presented below.

Router Asus RT-N10U

The characteristics of the router used for transferring data:

- Network Standard
  IEEE 802.11b, IEEE 802.11g, IEEE 802.11n, IEEE 802.11d, IEEE 802.3, IEEE 802.3u, IEEE 802.11i, IEEE 802.11e, IPv4, IPv6
- Data Rate
  802.11b: 1, 2, 5.5, 11Mbps
  802.11g: 6,9,12,18,24,36,48,54Mbps
  802.11n: up to 150Mbps
- Antenna
  Detachable 5 dBi antenna x 1
- Operating Frequency
  2.4GHz
- Encryption
  64-bit WEP, 128-bit WEP, WPA2-PSK, WPA-PSK, WPA-Enterprise, WPA2-Enterprise, Radius with 802.1x, WPS support
- Management

UPnP, DNS Proxy, DHCP, DDNS, Virtual Server, DMZ, Universal Repeater, System Event Log

- VPN Support
  - IPSec Pass-Through
  - L2TP Pass-Through
  - PPTP server
- WAN Connection Type
  - Internet connection type: Automatic IP, Static IP, PPPoE (MPPE supported), PPTP, L2TP
- Ports
  - 1 x RJ45 for 100 BaseT for WAN, 4 x RJ45 for 100 BaseT for LAN, Support Ethernet and 802.3 with max. bit rate 100 Mbps and auto cross-over function(MDI-X)
  - USB 2.0 x 1
- Power Supply
  - AC Input: 100V~120V(50~60Hz) for US type
  - DC Output: 12 V with max. 1 A current
- OS Support
  - Windows® 8, 32bit/64bit
  - Windows® 7, 32bit/64bit
  - Windows® Vista, 32bit/64bit
  - Windows® XP, 32bit/64bit
  - Mac OS X
  - Linux
- Router Specific Features
  - 3G/4G data sharing Printer server AiDisK Multiple SSIDs Parental Control

Vodafone K4510 Modem

Similar to a USB Modem, Vodafone Huawei Mobile Broadband USB Sticks will allow connecting the laptop or desktop computer over the mobile network, so you can browse the web, collect emails or receive and send SMS text messages.

Huawei K4510 USB Modem Specs:

HSDPA CAT 24, 28.8Mbps DPA, HSUPA 5.7Mbps
GSM quad-band: 850 / 900 / 1800 / 1900
UMTS quad-band: 850 / 900 / 1900 / 2100
Receive diversity
External Antenna
Micro SD card slot
Plug and play

Modem RCS&RDS Huawei E3131

HSDPA 21.6 Mbps/ HSUPA 5.76 Mbps
UMTS/ HSUPA/ HSPA+/ GSM/ GPRS/ EDGE
Micro SD card slot; External Antenna

B.2.2 UPB measurement system

The measurement system comprises of several physical (mobile) PMUs deployed in the Romanian electricity network and connected either in the utility company's intranet or directly to internet via 3G modem connection (in isolated areas where the utility company's intranet had no coverage) and two PDC-dedicated computers running the openPDC software version 2.0.133.0 as described in [11].

- One of them is used productively for storing the measurements archive.
- The second is used only in specific situations, when the data link between the on-field location of the PMU is too weak to support real-time transfer rates.

In addition to the above equipment type, there is one Asus RT-N10U router (running custom tailored OpenWRT based firmware) for each group of PMUs connected together.

The router's custom firmware has been modified to suit our needs using the OpenWRT build root tool-chains and the cross-compiled for the router's Broadcom BCM47XX processor [14].

The measurement set-up currently active at UPB consists in 4 Arbiter PMUs, one microPMU (PQube3 with synchronization capabilities) and a SmartMeter with extended capabilities (SMX). Their technical characteristics together with those of the communication modules are presented in the previous section.

Data can be downloaded using a dedicated Java web application installed on the data server @MicroDERLab in .csv formats. The usual quantities that can be extracted using the PDC platform and a dedicated interface are: frequency, RoCoF, voltages and currents (amplitudes and phases, all three phases and components).

A print screen with the platform (described in [13]) can be found in Figure B.9.

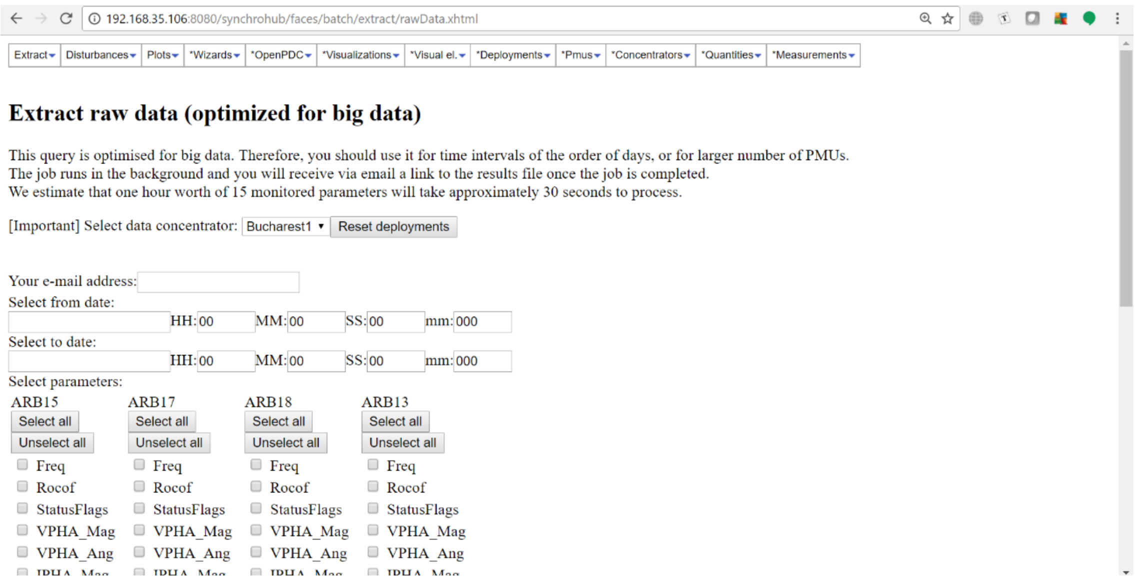


Figure B.9. Java web application for data collection screenshot (4 PMUs connected to the server)

The communication infrastructure is described in [12, 14] and is summarized in section B2.2.1.

B.2.2.1 Communication infrastructure for the UPB lab set-up

B.2.2.1.1 Description of the Concept

The set-up at UPB has many particularities, one of the most important in this case being the mobility/flexibility of the solution. As it can be seen in the following sections, the same PMUs were used in various locations allowing a wider image of the grid with a minimal infrastructure. As such, the proposed solution presents some challenges that in the case of a well-established and non-flexible classic WAMS network are not present, since the PMUs and the PDC are often located in the same intranet, or the network can be reconfigured to integrate the measurement layer.

However, in case of UPBs mobility-oriented deployment the target network infrastructure cannot be reconfigured easily, because of strict network access policies and security auditing not allowing opening inbound ports. Therefore, a sustainable way to connect the remote PMUs to UPB on-premises PDCs must fulfil some requirements [11]:

- The C37.118 connection from the PDC to a random PMU must be first tunneled from inside the perimeter network of the company where the PMUs are deployed via VPN connection (using small one low-cost programmable router for each deployment bridgehead, see Figure B.10)

- Must be autonomous regarding connection failures
- Must be remotely manageable

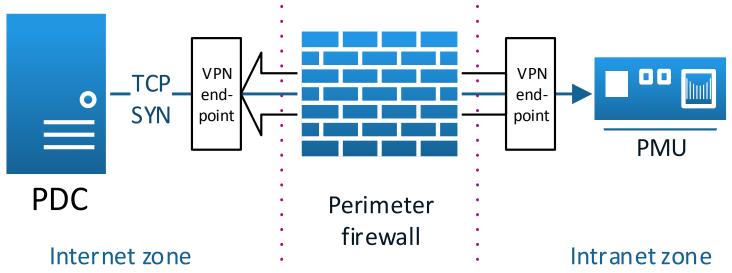


Figure B.10. Implementation of VPN tunnelling [12, 14].

Due to the need to integrate a communication solution with the existing infrastructure (existing network topology, addressing type and access control, network access policies already in place) each new deployment request is unique. The PMU acts as a TCP server listening on port for connections from the PDC to start delivering the measurement data based on the C37.118 [8] protocol used by the PMUs to communicate with the PDC. This makes the deployment even more difficult, since the PDC that collects all the data is located on one location (UPB Laboratory in this case) and the PMUs are located on the requesting company's premises (i.e. DSO, TSO). Usually this would require that the company reconfigures their firewall to allow inbound TCP connections from our PDC (located outside their perimeter) towards their internal network but this is not possible in most cases (Figure B.11).

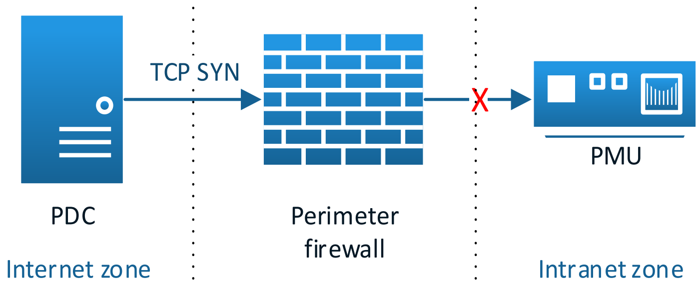


Figure B.11. Network access policy prevents the C37.118 protocol form being initiated from outside towards inside entities [12, 14].

B.2.2.1.2 Data topology

The data topology is multi-site based, given the fact that each PMU or group of PMUs deployed on field connects to main network via VPN tunnels (Figure B.12). This environment is typically difficult to maintain if permanent changes are occurring. However, using the openVPN software for implementing the tunneling, it manages to push any routing information changes to all VPN endpoints sitting on-field deployed routers, which then tunnel back the C37.118 [7] connections from the on-field PMUs to our PDC for archival.

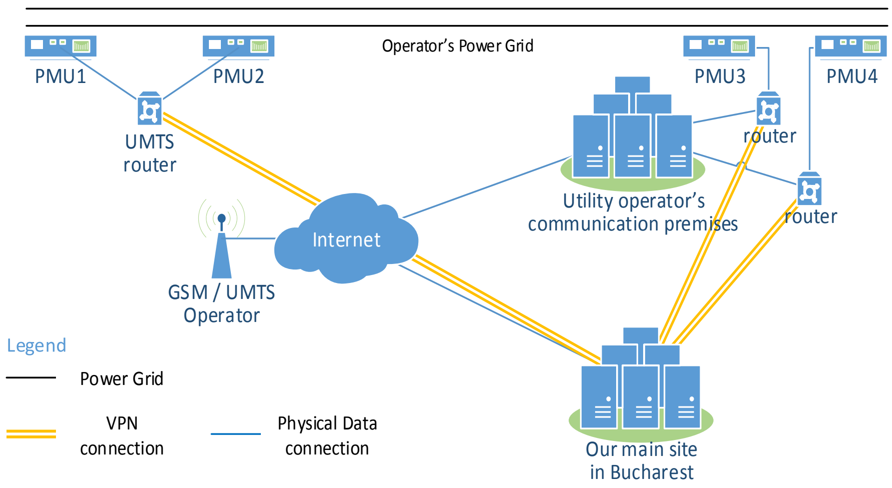


Figure B.12. Our overall data topology deployed on field [12, 14].

The VPN tunnel [12, 14] consists in a TLS connection, which is encrypted by our own PKI certificates with 2048 bits RSA public keys. To facilitate the rapid deployment, the public certificate of the root certification authority was embedded into the custom router firmware. This way the provisioning process involves only assigning the IP addressing loading the client certificates and the static shared secret key file into the router's *nvram* partition.

B.2.2.1.3 Security of Data transmission

The data connections between the PMU, openPDC at site and data centre are mainly over IEEE C37.118 protocol [8]. This protocol does not have an encryption layer; therefore, handling the security is left to the implementation solution.

In our case, the envisioned Data transmission options are:

- Via local wireline/Wi-Fi internet access if provided by the deployment site
- Over 3G, if there is 3G signal in the area
- Future connectivity backup solution (explained below)

Security over the first two options is being covered by using a VPN connection from the source (on site PDC software) to the centre.

Provided that the 3G data signal is not ubiquitous and there are gaps in the coverage, the monitoring solution requires a backup option. For this the proposed solution in [14, 15] is to use the modems over voice channels. This backup solution targets only the Basic Broadcast data of the PMU, which requires up to 2000bps (Table B.1). As the voice channels are internal to the telecommunication operator's network and in peer-to-peer mode, the connection is considered much safer compared to those over internet. When improved security is required, an additional layer of encryption is proposed by using the socat and openssl tools for encrypting the data in transit, on either Linux or in Windows via Cygwin. The keys and certificates already explained in the section 0 are being used also for this openssl instance.

The details on the measured parameters being recorded for each data type can be found in technical specifications of each equipment.

Table B.2. Data Connection Speeds per Configuration [6]

Data Type	Bandwidth (bytes/sec)
Basic Broadcast	24 - 244
Energy Broadcast	22 - 182
Harmonics Broadcast	92 - 2492
Phasor Broadcast	920
Summ Harm Broadcast	20 - 140

Waveform Broadcast	7960

B.2.2.1.4 Security of openPDC [13]

When the network or physical access to the computer where the PDC software and its database/files are being stored does not match the level of security targeted for the solution, openPDC's security layer can be used. The steps to set it up are intuitive and provided from the installation time.

This way, once the setup is being initialized, openPDC provides 3 options for user accounts:

- Local DB Authentication
- Windows account definition with Local System credentials
- Account on Microsoft Active Directory

The third option case, which is recommended in institutions with an infrastructure for access permissions, allows more secure and flexible options. This way the administrator can decide which Active Directory Domain users should be assigned the View role, edit role or the Administrator role.

View role allows checking recorded PDC data. Edit role allow activities like enabling/disabling the recording, changing mappings between input devices and historians, etc. Administrators can do all be previous activities, plus modifying the permissions of the users, adding as well as removing users.

Data recoding being done on the disk can be either in files or in a database. Available database options are: SQL Server, MySQL, SQLite, and Oracle. If the premises are not providing the physical security at the level required, additional steps can be taken for encrypting the disk on which the database files are being stored, with truecrypt or bitlocker solutions. In our situation, this additional level of security was not required.

B.2.2.1.5 Security on the PMU device [12]

The PMU device keeps proprietary data and in some cases bound to Non-Disclosure Agreements. For this reason, it is important to secure data starting from the source - the PMU itself.

The software on the 1133A Power Sentinel has an optional security layer. When disabled, the "anon" user has full access to the device. When security is enabled, by default there are two main users being used: "anon" and "admin". The "anon" user allows anyone to download the data. The admin account has the highest level of access. Both anon and admin accounts come with default passwords which are present in the published documentation. For this reason, it is advisable be changed from the initial setup of the PMU.

The security options provided by the devices, software and networks used do match the level of security targeted for the current project, and it also keeps a good balance with the flexibility and usability of the system.

B.2.2.2 Frequency monitoring

Figure B.13 shows the template of the frequency measurements after synchronizing the data from multiple PMUs.

	Babadag1		Babadag 2		Cheia		Bucuresti	
Date and Time	f [Hz]	rocof[Hz/s]	f [Hz]	rocof[Hz/s]	f [Hz]	rocof[Hz/s]	f [Hz]	rocof[Hz/s]
2014-04-01 00:00:00:020	50.0148	5.96E-04	50.0163	0.0084448	50.0156	0.0032131	50.01498	-0.002757
2014-04-01 00:00:00:040	50.0152	0.01788139	50.0163	-9.50E-04	50.0143	-0.0642799	50.01507	0.0040978
2014-04-01 00:00:00:059	50.0158	0.02883375	50.0157	-0.031422	50.0129	-0.0743661	50.01517	0.0054389
2014-04-01 00:00:00:080	50.016	0.01303852	50.0145	-0.056641	50.0128	-0.0027474	50.01535	0.0084937
2014-04-01 00:00:00:100	50.0159	-0.0041723	50.0138	-0.036338	50.0135	0.0329036	50.01546	0.0057369
2014-04-01 00:00:00:120	50.0156	-0.0190735	50.0144	0.0283821	50.0137	0.0142772	50.01552	0.0029057
2014-04-01 00:00:00:140	50.0148	-0.0391155	50.0157	0.0679307	50.0141	0.0188686	50.01529	-0.011697
2014-04-01 00:00:00:160	50.0144	-0.0180304	50.0164	0.0347733	50.0154	0.0618212	50.01493	-0.017881
2014-04-01 00:00:00:179	50.0146	0.00983477	50.016	-0.022126	50.0159	0.0262726	50.01495	0.0012666
2014-04-01 00:00:00:200	50.0152	0.02704561	50.0148	-0.056499	50.0149	-0.0490807	50.01516	0.0103563
2014-04-01 00:00:00:220	50.0156	0.0230968	50.0146	-0.012354	50.0146	-0.0168756	50.0153	0.006929
2014-04-01 00:00:00:240	50.0157	0.00394881	50.015	0.0187033	50.0157	0.056969	50.01518	-0.005737
2014-04-01 00:00:00:260	50.0155	-0.0084192	50.0152	0.0131782	50.0161	0.0207033	50.01483	-0.017509
2014-04-01 00:00:00:280	50.0152	-0.0186265	50.0151	-0.008512	50.0155	-0.0332203	50.0146	-0.011697
2014-04-01 00:00:00:300	50.0149	-0.0107288	50.0146	-0.022098	50.0146	-0.0420865	50.0145	-0.004917
2014-04-01 00:00:00:320	50.0146	-0.0174344	50.0146	-4.77E-04	50.0145	-0.0037253	50.01459	0.0043958
2014-04-01 00:00:00:340	50.0144	-0.0103563	50.0151	0.023786	50.0154	0.042785	50.01455	-0.002012
2014-04-01 00:00:00:360	50.0145	0.0051409	50.0156	0.0235485	50.0161	0.0349246	50.01436	-0.009388
2014-04-01 00:00:00:380	50.0147	0.01095235	50.0152	-0.015667	50.0158	-0.012992	50.01433	-0.001714
2014-04-01 00:00:00:400	50.0149	0.0076741	50.0138	-0.071155	50.0156	-0.0136904	50.01431	-7.45E-04
2014-04-01 00:00:00:420	50.0147	-0.0073016	50.0126	-0.061519	50.017	0.0742543	50.01429	-9.69E-04
2014-04-01 00:00:00:440	50.0143	-0.0209361	50.0127	0.0053993	50.0186	0.0766385	50.01392	-0.018626
2014-04-01 00:00:00:460	50.0138	-0.0266731	50.0137	0.0493112	50.0177	-0.0463333	50.01331	-0.030771
2014-04-01 00:00:00:480	50.0133	-0.0216067	50.014	0.016219	50.015	-0.1338497	50.01298	-0.016391
2014-04-01 00:00:00:500	50.0133	-0.0034273	50.0131	-0.044876	50.014	-0.0464357	50.013	0.0011176
2014-04-01 00:00:00:520	50.0134	0.00678003	50.0122	-0.047765	50.0138	-0.0114925	50.01332	0.0163913
2014-04-01 00:00:00:540	50.0135	0.00499189	50.0122	-4.89E-05	50.0131	-0.0380911	50.01343	0.0052154
2014-04-01 00:00:00:559	50.0136	0.00283122	50.013	0.042282	50.0123	-0.037523	50.01325	-0.008941
2014-04-01 00:00:00:580	50.0135	-0.0032038	50.0134	0.01946	50.0119	-0.0197254	50.01316	-0.004694
2014-04-01 00:00:00:600	50.0133	-0.0088662	50.0128	-0.03157	50.0117	-0.0117999	50.0131	-0.00298
2014-04-01 00:00:00:620	50.0131	-0.0111759	50.0119	-0.044694	50.0123	0.0296254	50.01318	0.0041723
2014-04-01 00:00:00:640	50.0128	-0.0122935	50.0118	-0.002924	50.0128	0.0248663	50.01316	-9.69E-04

Figure B.13. Data for frequency analysis recorded using the system implemented at UPB [12]

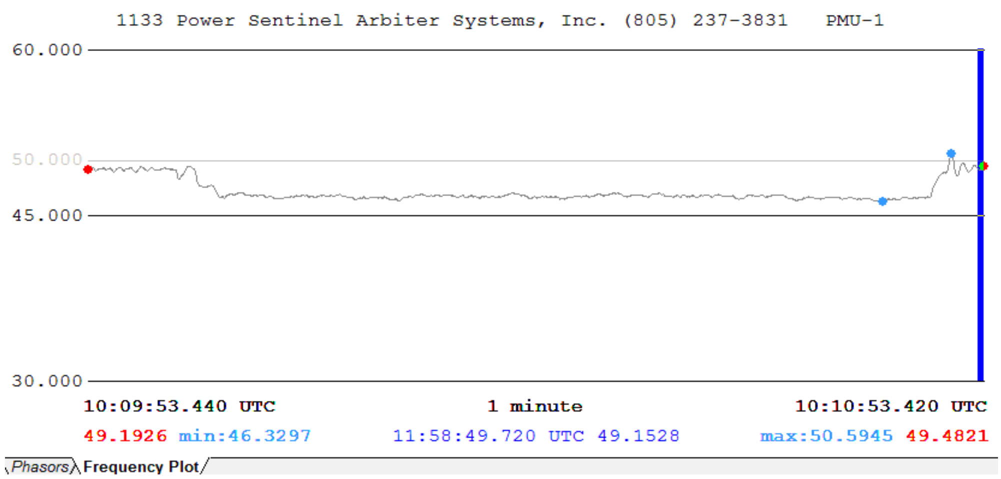


Figure. B.14. Frequency variation during tests (screenshot from Arbiter interface)

The tests have shown that the measured data is very accurate, despite the always changing measurement environment parameters have been performed on the configuration. The results have shown so far that this type of deployment offers the same measurement outcome as if a complex WAMS would permanently be installed.

The platform can be implemented quickly, in a few of minutes, after the topology and environment has been agreed on. This makes it very cost effective, since the purchase of additional equipment is not necessary. With some minor adjustments in terms of assessing the usage and billing, it can be considered a “measurement as a service” offering for small or medium smart-grid operators, in case they need a non-permanent WAMS-like synchronized measurement system.

The general configuration of the lab set-up is presented in Figure B.15 with a connection detail for the PMU/microPMU in Figure B.16.

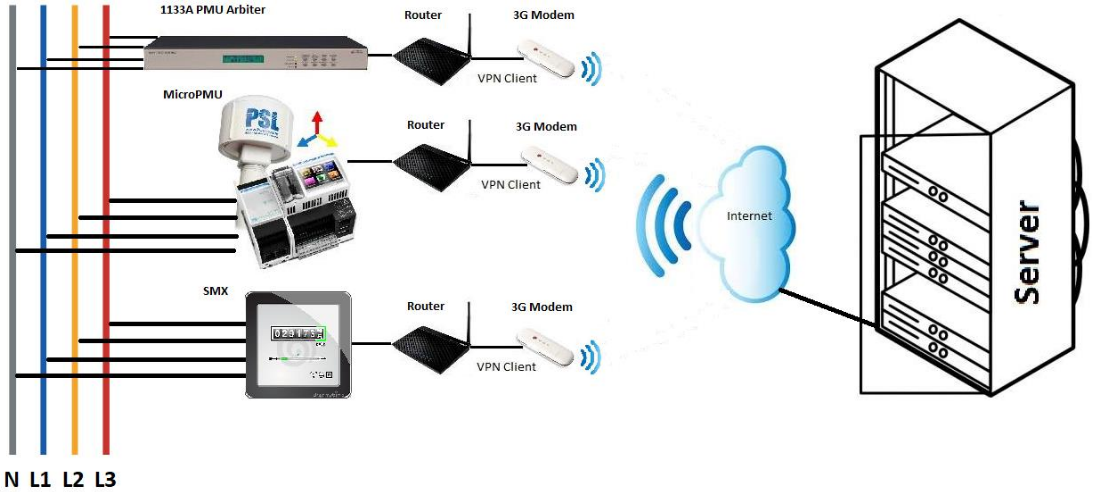


Figure B.15. Lab set-up at UPB with PMU, microPMU and SMX SmartMeter

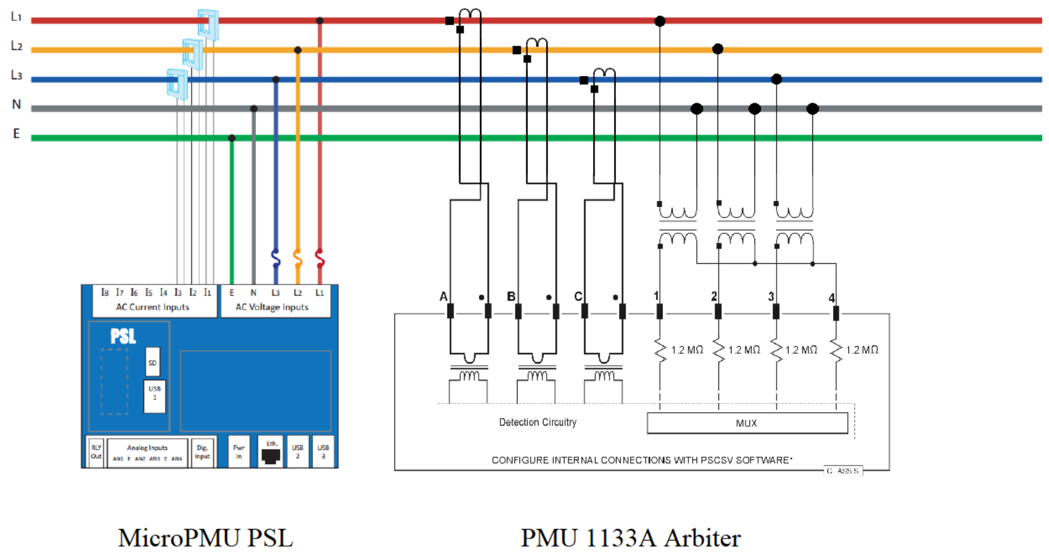


Figure B.16. PMU/microPMU connection.

B.3 Pilot projects in power system monitoring and operation

B.3.1 WAMS in Switzerland

For the first time, the power system frequencies of several locations in Europe are being time-synchronized and made publicly accessible with a high degree of precision in one common system. The measuring devices equipped with GPS receivers in each of the substations calculate the frequency and deliver it in real time together with other time-stamped data accurate to the microsecond. These are then collected at Swissgrid in Laufenburg, superimposed on one another and published [3].

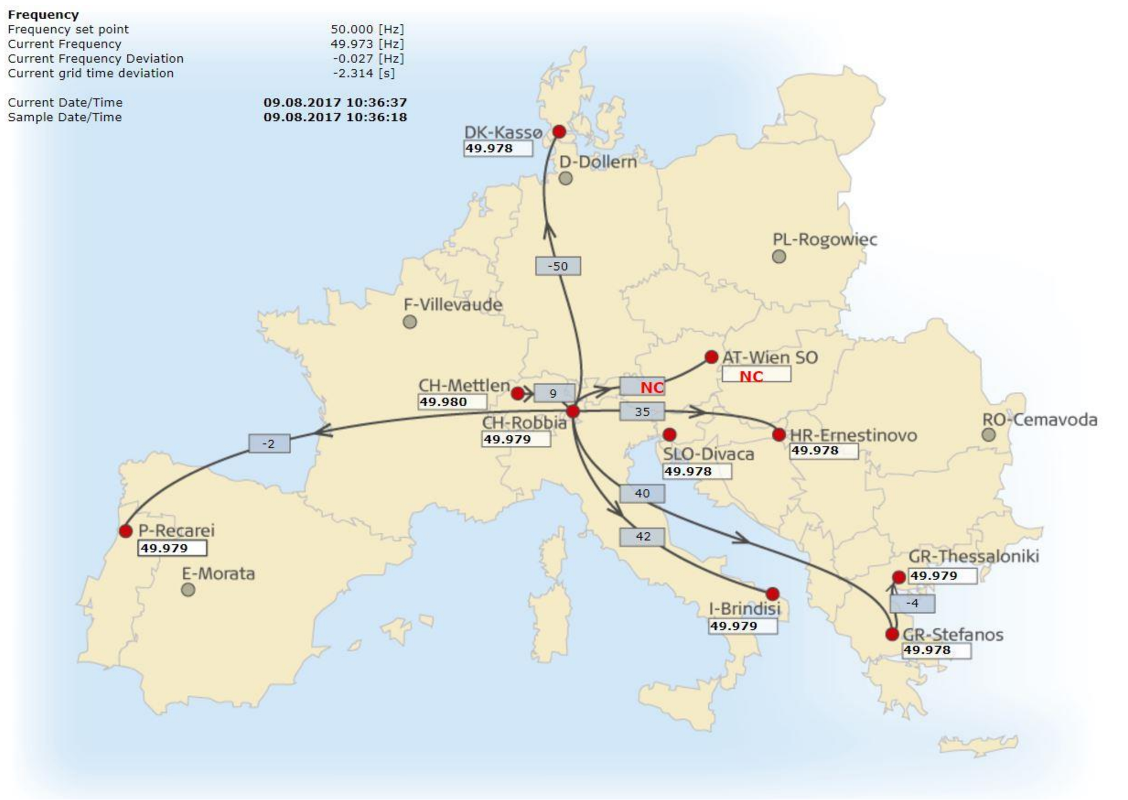


Figure B.17. Wide Area Monitoring in Switzerland [3].

The differences in frequency that are typical of the system, in the magnitude of the third decimal place, indicate what is known as the “breathing of the European interconnected power system”. Both long-term and short-term deviations from the nominal frequency of 50 Hz provide the experts at Swissgrid with indicators of the current grid status. Wide Area Monitoring is therefore an additional tool for guaranteeing the security of supply in Europe.

In addition to frequency, each measuring device also provides the current voltage angle in real time. Using the difference between any two measured voltage angles it is possible to represent in approximate terms the load flows between the two measuring points. However, as it is a meshed grid and hence the entire topology is considered, these data provide only indicators of the power flows at any moment. A sudden change in the angle difference could, however, point to a transmission line outage, for example.

The deviations in the grid frequency on the European interconnected power system are so small that the nominal frequency of 50 Hz is still used today as a timer in many cases. Despite the extremely slight deviations, errors of a few seconds a day may still occur. This is also used as a further quality indicator of the power system state.

In order to keep this difference as small as possible and to continuously adjust the grid time to the coordinated universal time (UTC), Swissgrid records the deviations on behalf of the ENTSO-E electricity transmission association and coordinates the necessary corrections.

B.3.2. WAMS in Great Britain

The deployment of the first WAMS to monitor the entire power system in real time was the responsibility of the visualization of real time system dynamics using enhanced monitoring (VISOR) project. The VISOR project is a GB innovation project led by SP Energy Networks (SPEN) that brings together the three GB transmission system owners (SPEN, National Grid and SSE), the GB system operator (National Grid), researchers (The University of Manchester) and vendors (GE Grid Solutions). The core goal of VISOR is to create the first WAMS that monitors the entire GB system and then to use this WAMS to showcase the tangible benefits of WAMS applications to GB system. VISOR WAMS will have the following roles [5]:

- Monitoring and alarming for subsynchronous oscillations (SSO) in the frequency range of 0.002–46 Hz.
- Localizing the source of SSO.
- Dynamic model validation.
- Reducing the impact of uncertainty on security limits.
- Hybrid state estimation (HSE).
- Line parameter estimation (LPE) using PMUs.
- Optimal placement of synchronized measurement
- Technology (SMT) for monitoring SSO.
- Laboratory testing of SMT.

Mostly, most of the measurement devices in the VISOR WAMS will be PMUs. The schematic of VISOR WAMS is presented in Figure 4. An innovative feature of the VISOR WAMS is that it includes the first live trial of a 200 Hz WMU that is fully C37.118.2 compliant, which will be used to monitor SSO up to 46 Hz in real time. Once complete, the VISOR WAMS will receive real-time data.

The GB wide WAMS that VISOR is deploying builds upon previous WAMS deployments within SPEN and NGET with the goal of providing visibility of all three-transmission owner (TO) areas to the GB SO. Initially the communication between each of the three new TO level data centres and the SO level data hub will use an IPSec link. However, during the course of the project a MPLS link will be established between the SPEN data centre and the data hub to accommodate the larger amount of data that will be streamed from this TO network.

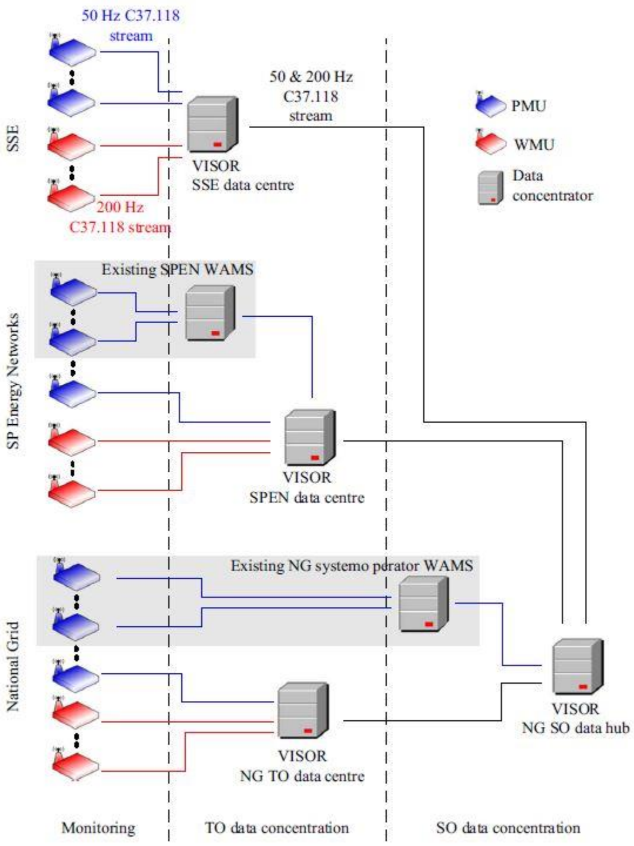


Figure B.18. Schematic of VISOR WAMS [5]

B.3.3 WAMS in Italy

Wide Area Monitoring system is also used in Italy since 2013 as an additional tool for power system operation and analysis. The need for the comprehensive observation of highly loaded transmission corridors was one of the driving forces behind this. A tool with respect to interarea oscillations able to monitor the system's stability was another important target [32].

Figure B.19. Monitoring phase angle in Italy [32].

A typical control room application, in which a dynamic coloured map displays the value of a quantity selected by the operator, e.g. the relative phase angle, the voltage magnitude or the frequency is presented in Figure B.19. Elements like arrows between nodes, which indicate the direction of the active and reactive power flows (blue, respectively purple arrows), or arrow thickness, which varies according to the angle difference have the role to offer more detailed information in the graphic. Another explicitly marked elements are the phase angle differences between the nodes. If the geographical display is included in this scheme, more visualization and control displays can be shown, for example, results of the oscillatory analysis function, or the evaluation of the voltage magnitude plots. Configuration data such as visualization options and alarm threshold settings are contained in other displays. In case of threshold violations, e.g. in the case of high/low voltage magnitude, specific alarms are automatically triggered.

B.3.4 WAMS in Germany

The Wide-Area Monitoring System, SiGuard – PDP is being used by E.on Netz, one of the four German TSOs. The SiGuard – PDP software helps the network operator to obtain an overview of the state and stability of the power system. The architecture of the system is presented in Figure B.20, and consists of several PMUs connected with a set up point via a fast communication link [33].

The up-to-date measured values from the connected PMUs are sent via communication channels to the Phasor Data Concentrator (the central component of the system). The sent values can be current and voltage phasors, frequencies, frequency changes, etc. These are always written into the archive, and presented to the operator through the graphical user interface (HMI). Several actions such as monitoring the communication links, the quality of the PMU data and the internal functions are completed by the Phasor Data Processing System. The user can choose between direct observation for the online data and analysis of archive data in offline operation.

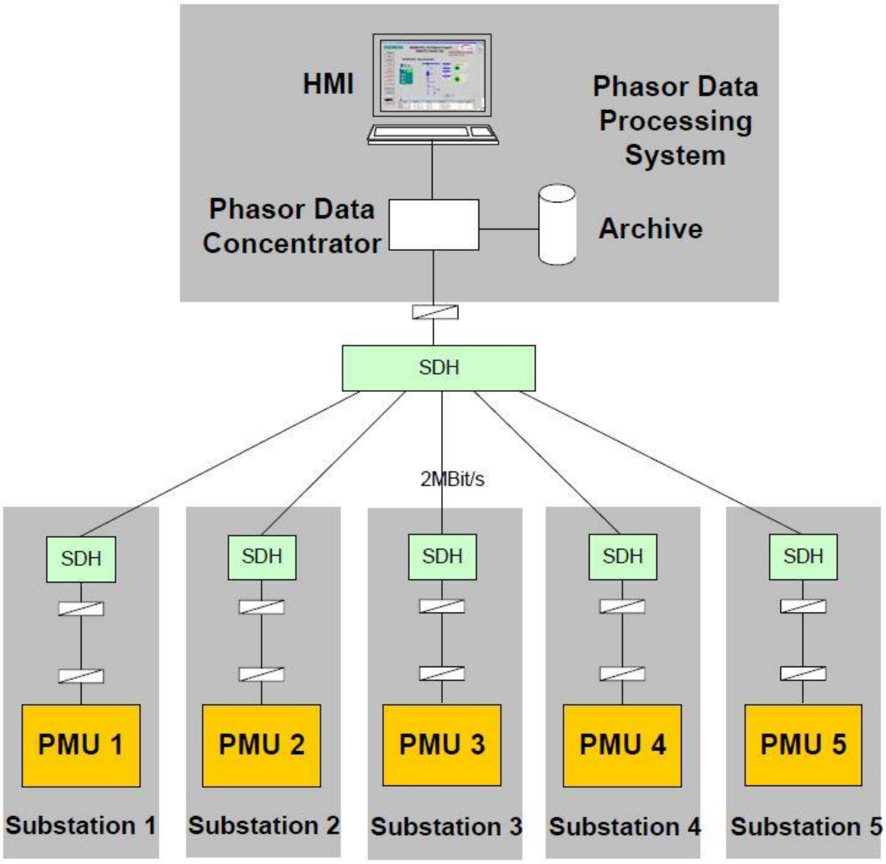


Figure B.20. Configuration of a Phasor Data Processing System at E.on Netz [33].

The structure of the main monitor of SiGuard is presented in four parts [33]:

- *Power System Status*: This tool shows a cumulative index for the overall state of the monitored network. All the measured values that come from the PMUs are sent into calculation. The status of the network is more critical when the curve is more near the dotted limit values. In order to allow quick and easy recognition, the colour of the Power System Status Curve changes from black to red when at least one measured value violates a limit.
- *Geographical view*: Here, the monitored transmission network, including lines and substations is geographically presented. This is a very useful tool for the user, because thanks to the colouring of the network, a region with problems can be immediately distinguished. In Figure B.21 it is shown an example in which the colour of the squares represents the voltage status (blue=OK, yellow=limit value 1 violated, red=limit value 2 violated). If the colour of the network changes to gray, it means that the communication with the PMU is interrupted.
- *Display area for measured values*: In this area the time characteristic of the selected phasors or other measured or calculated values is shown. The selection is made from the list of all measured values in the configuration area. An example of such a window is shown in Figure B.22.
- *Configuration area*: This is the place where all available measured values of the connected PMUs are listed. The measured values are split in two: Phasor (can also be displayed time characteristics) and analog (only time characteristics). A so called 'PV-Curve' or 'nose curve' can be calculated and displayed, as shown in Figure B.23.

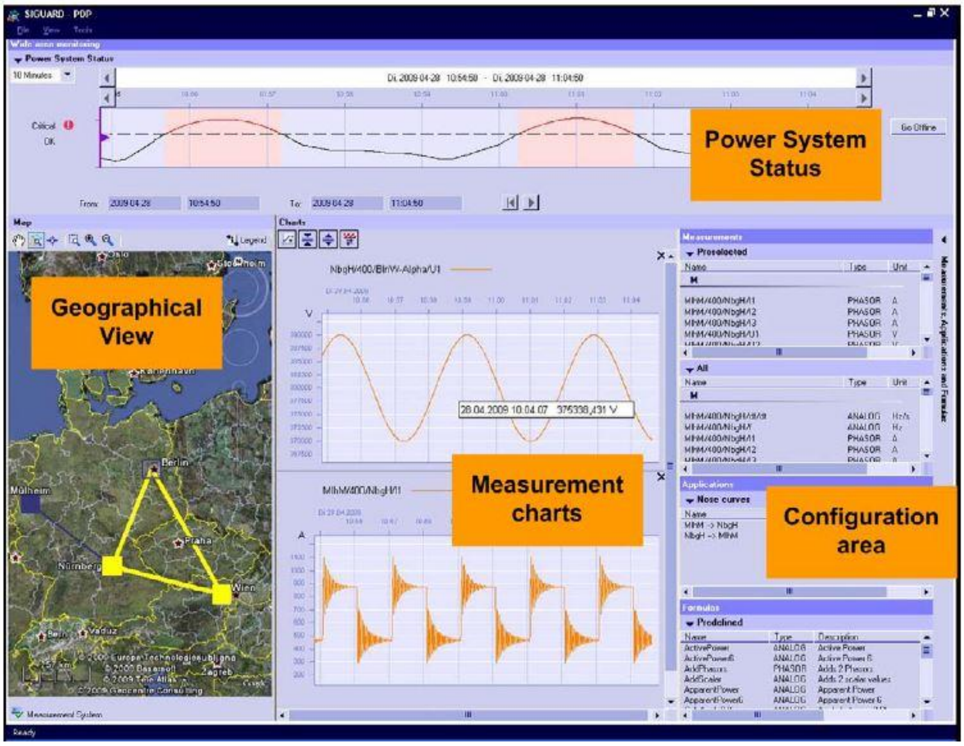


Figure B.21. Architecture of the HMI of SiGuard – PSA [33].

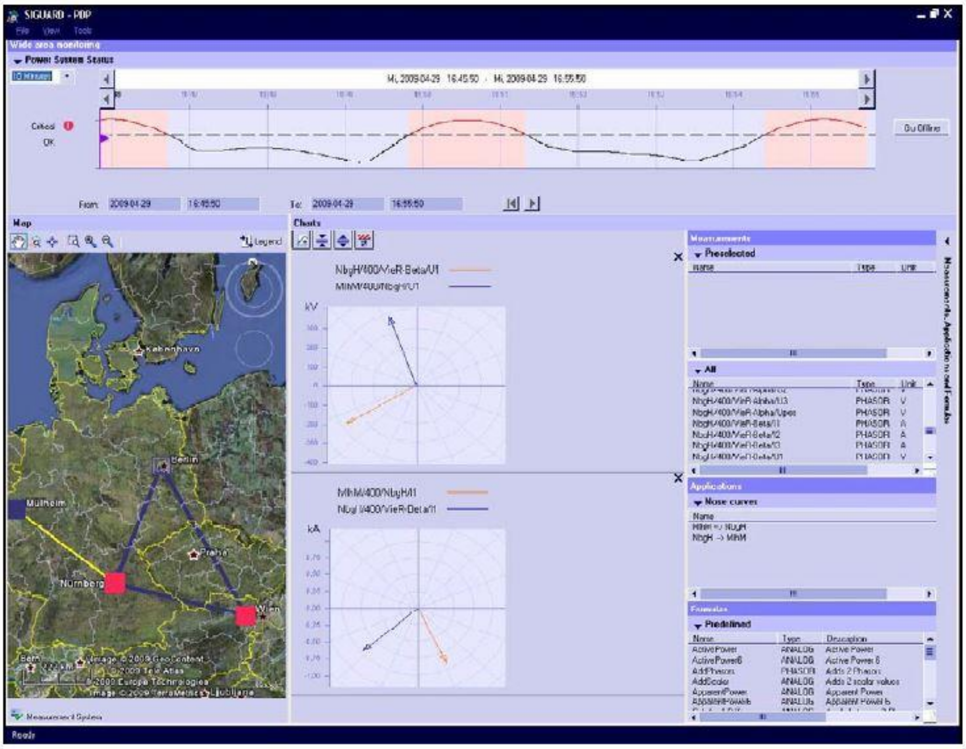


Figure B.22. Area of measured values [33].

Annex C. Analysis of frequency measurements in the Romanian power system

C.1 Introduction

This section includes several cases of data analysis using frequency data from PMUs and data from the microPMU and SmartMeter for comparison purposes.

The analysis includes:

- Comparative illustration of the frequency in different nodes in Romania (at different voltage levels)
- Comparative illustration of the frequency recorded with different equipment in the same LV node
- Time variations, histograms and CDFs for a full day of recordings in July (chosen bases on the events that took place at national grid level to highlight the impact of them on the local measurements). Also, for one of these events, localized time variations, histograms and CDFs are presented.
- Impact of time data aggregation (as defined in IEC61000-4-30).
- Communication delays

The specific deployment of PMUs (and other equipment) will be briefly described for each case.

C.2 Frequency calculation

Monitoring the power transfer in LV and MV networks is mainly done in the power quality framework. Standards [17] are silently assuming steady state operation with nearly constant frequency. The upper limitations for deviations of frequency and voltage (rms values) are applied to values obtained from a successive aggregation of measurement data obtained from long-term observation. A compromise between the end-user needs for information and the amount of data resulting from averaging over one period of the observed quantities waveforms is given by data aggregation over the time axis.

According to the standard [17], the aggregation method related to voltage measurement is the root mean square (rms) algorithm performed on quantities describing energy transfer under stationary conditions. The aggregation method uses 4 different time intervals: 200 ms (10 cycles for 50 Hz system frequency – as basic interval for the measurement process), and 3 s, 10 minutes, 2 hours as aggregation intervals. Aggregations are performed, with one exception for the frequency (exception that is relevant for this study), using the square root of the arithmetic mean of the squared input values [17]. Figure C1 shows the theoretical structure of the aggregation process based on simple averaging algorithm for time aggregation of information on frequency.

Typically, three categories of aggregation are encountered: package aggregation, cycle aggregation, and time-clock aggregation. The package aggregation is the 10-cycle time interval aggregation.

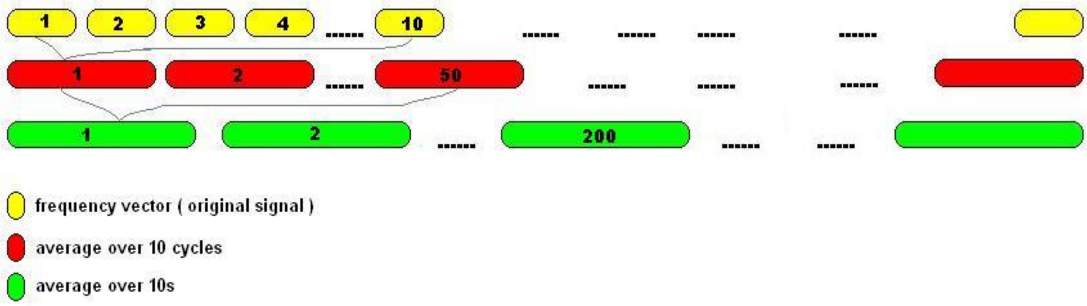


Figure C1. Time aggregation process according to [17] - for frequency data.

According to the standard, the time tag is the time at the end of the 10-min aggregation [17]. The 2-hour intervals measured data should be computed from twelve 10-minute time intervals.

For this study, the time intervals used for aggregation are: 200ms (10 cycles), 10 s (the interval set by the standard) and 10 minutes (in order to be able to compare data with other PQ information).

C.3 Communication delays

The fast transfer of the PMU measurements to the control centre is crucial for achieving real time control of power networks. For example, although the PMU reports synchrophasors every 20 ms, the delay that is introduced to the measurement data by the communication infrastructure may degrade significantly the information transfer in the control loop that includes the PMUs. In general, the transfer delay of the PMU measurements could be due to several factors, such as the communication medium that is used for transferring the measurements (fibre optics, 3G, Wi-Fi, phone line), the communication protocol (TCP, UDP, DNP3), the components of the communication infrastructure (i.e., routers, RTUs, etc.), and the Phasor Data Concentrators (PDCs) [12,18].

In the case that the communication delays from the PMUs to the processing unit (be that PDC or an upper layer) are large, the performance of the real-time applications that rely on the fast reporting rate of the measurements (i.e., dynamic systems) will be compromised. In this sense, the estimation of the delays that the PMU measurements experience is essential in a real-time application. Further, the knowledge of the delay will set the waiting time of the PDC that is used for collecting and time aligning the synchrophasors before forwarding them to the next layer [12]. However, given the complexity of the processes causing the delayed communication, for specific technologies and specified nodes, one can determine experimental cumulative distribution of delays for assessing their most likely value.

There is little information on actual delays caused by a 3G or 4G network to the PMU measurements. Although the use of other types of networks such as fibre optic, is more probable for transferring PMU measurements in WAMS, not all the substations in a large power system are equipped with fibre optics. Therefore, the use of a 3G/4G network could be a solution for such cases to transfer PMU measurements from the substation to the control centre.

On a 3G network experimental investigation of communication delays is reported in [37]. The data communication testing has been based on a procedure described in [12,18], and comprises of a device [10] able to register the timestamp of data packets as they arrive at the PDC. The sending equipment is a (mobile) PMU Arbiter 1133A Power Sentinel [7], which has been connected in the MV grid using the measurement wiring of the CT and can be assumed as an M-class device. The PMU is configured for TCP communication. The time delays are calculated from the timestamp of packets arriving at PDC (procedure accomplished using the Timetools device [10]) and the timestamp of the data frames as sent by the PMU. In this way, delay includes the internal time constant needed by the PMU to deliver the measurement data on the communication channel, the actual communication delay and the Network Interface Card delay of the server running the PDC. In the following, we will use the term “communication delay” for the result of these several random processes.

Table C.1 shows an example of PMU data frames delays corresponding to two nodes in the Romanian power grid: i) Cheia Substation (20/0.4 kV) and ii) Galati Substation (110/20 kV). In both cases a 3G communication ensured by a public provider has been used.

For the first case, the statistical variations (minimum, maximum and mean values over 10 s intervals), original registration of delays and empirical CDF for a full day of transmitted data in the case of the communication between the Cheia substation and the data server in the UPB laboratory. For the second case (the same information is presented for one hour. As it can be seen from Table 3 [28] and Figures C2 and C3 there are variations between the delay times not only between various locations (with significantly smaller values for the second location), but between different sections of the day in the same location.

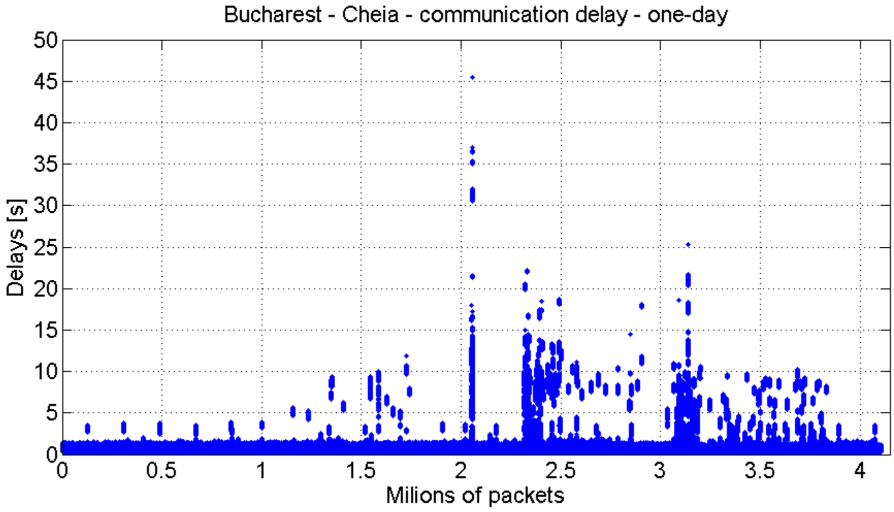
Table C.1. Sample of PMU Delays [in miliseconds] [28].

Location	Dist. PMU-PDC	Date	Interval	Min	Max	Mean	Std
Cheia (0.4 kV)	100 km	17.09.2015	00.40-00.50	193	1316	586.66	171.01
			00.50-01.00	170	1551	558.42	172.43
			01.00-01.10	166	1504	550.03	172.93
			01.10-01.20	184	1184	538.93	166.25
			01.20-01.30	183	1323	525.77	168.57
			01.30-01.40	125	5359	615.63	344.38
Galati (20 kV)	250 km	25.08.2015	08.20-08.30	160	750	308.82	65.05
			08.30-08.40	163	1444	308.51	70.99
			08.40-08.50	159	527	306.84	62.88
			08.50-09.50	160	2180	310.50	90.92
			09.50-10.00	163	535	307.53	63.77

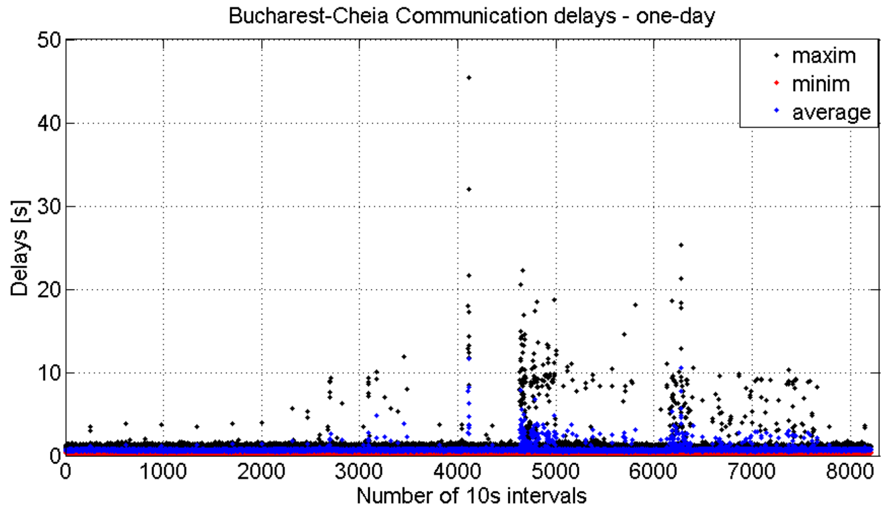
A common architecture for transferring the PMU measurements from the substation level to the control centre is shown in Figure B.10. Based on this multi-layered architecture, the PMU measurements are transferred from the substation level to the second layer where they are concentrated by the PDCs and then to the control centre for being processed by several applications. It is therefore evident that the PMU data are subject to delays due to the communication network and the process followed in the PDC. More particularly, the functionalities of a PDC are the time alignment of phasor measurements coming from multiple PMUs, the rejection of bad or time-delayed phasor measurements, and the forwarding of a set of phasor measurements with the same time tag to the upper layer of the measurement system (in this case the control centre) [10].

The delay due to the communication network can be considered by setting a maximum waiting time to the PDC which essentially determines the time that the PDC will wait the measurements with the same time tag to arrive, before sending the time aligned measurements to the control centre. In the case where the delays of some PMU measurements are larger than the PDC waiting time then the PDC will forward an incomplete measurement set to the control centre and their most recent ones that are available in the control centre will replace the missing measurements.

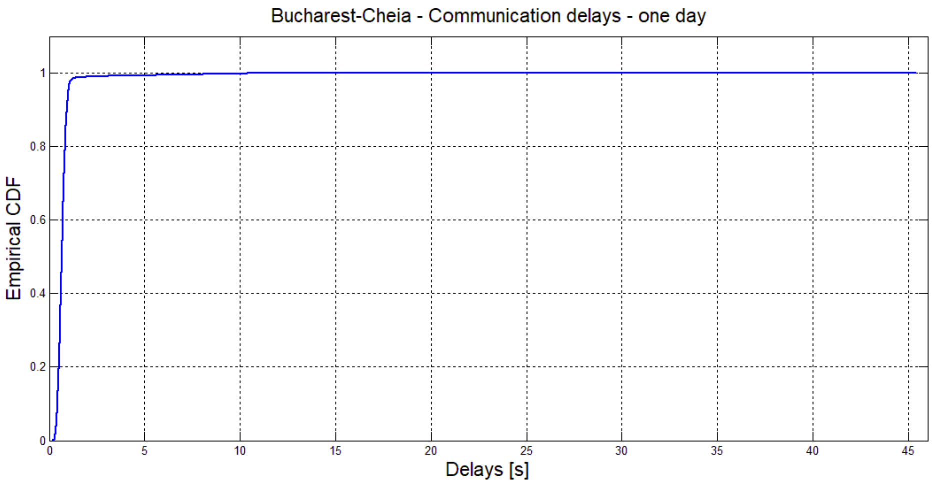
Both the incompleteness in the measurement set, as well as the delayed arrival of the measurements to the control centre, affect the accuracy of a real-time state estimation scheme, especially in the presence of faults, in the power system. On the one hand, a small waiting time will result in the loss of many PMU measurements (in case of a large measurement delay), while a large waiting time will affect the real-time response of a real-time application. Therefore, the setting of the PDC waiting time is a trade-off between the data set completeness and real-time response. Further, the proper determination of the PDC waiting time implies that one can accurately estimate the communication delays for each PMU-PDC channel. However, this is not possible, since communication network delays do not follow a consistent behaviour [7, 20]. Further, diverse types of communication networks (e.g., fibre optics, 3G or 4G networks, phone lines) result in delays with different magnitudes, following several, incompletely known, superimposed processes. For instance, it is expected that PMU measurements that are transferred through a fibre optic network will have a considerably smaller delay than other PMU measurements that are transferred through a 3G network. Therefore, it will be likely that in a large power system PMU measurement from different areas will be transferred to the control centre using several types of communication networks and thus PMU measurements will experience different delays.



a)

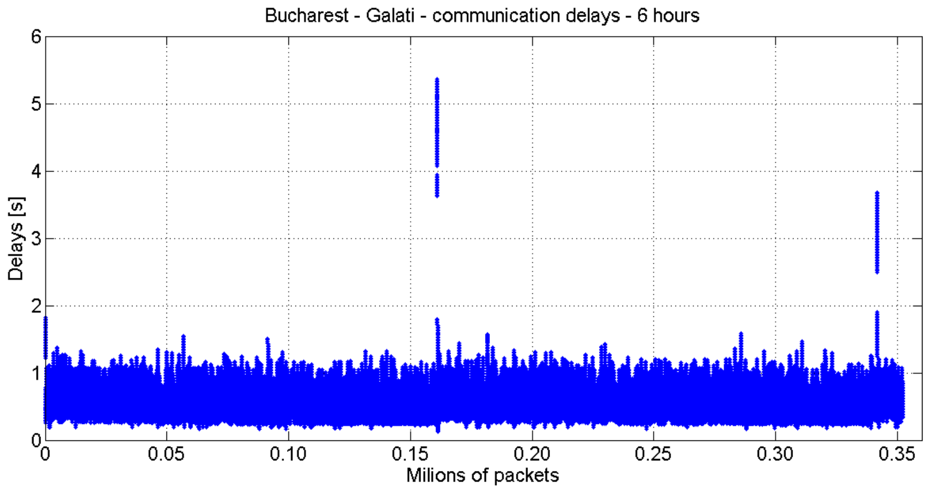


b)

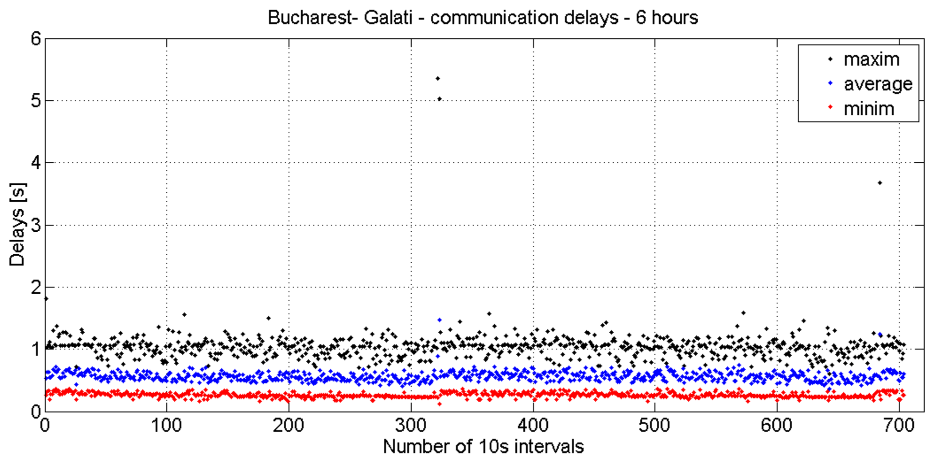


c)

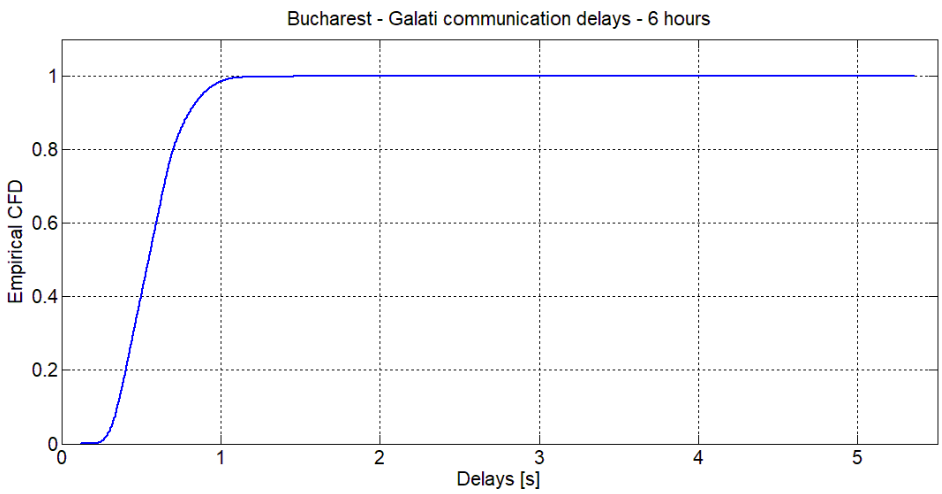
Figure C.2. PMU delays from Cheia – one-day interval: a) original data; b) mean, minimum and maximum values calculated for 10 s intervals; c) empirical cumulative distribution function.



a)



b)



c)

Figure C.3. PMU delays from Galati – 6-hour interval: a) original data; b) mean, minimum and maximum values calculated for 10 s intervals; c) empirical cumulative distribution function.

C.4 Frequency monitoring

C.4.1 Case 1: Frequency monitored in various locations in the Romanian grid

This case is presented mainly to show that in steady-state conditions the frequency monitored in distinct parts of the country (and at different voltage levels) has the same variation.

For the first test case 4 PMUs are placed in distinct locations and at different voltage levels. Two PMUs were in Babadag at the connection point of two wind farms, one for a small farm of about 8 MW and at the 20 kV voltage level and the other at the connection point of a larger wind farm of about 36 MW at the voltage level of 110 kV. The other two PMUs are connected in distribution networks at a voltage level of 0.4 kV, one in Cheia, and the other in Bucharest (in the laboratory. It is important to consider that UPB network is operating close to microgrid conditions).

For the three PMUs installed in at the utility side, in Babadag and in Cheia substations, we present the single line diagrams of the substations and point in red the PCC of the synchrophasors.

Using data from these PMUs, it is possible to monitor and compare quantities from different measurement points in the Romanian grid and for different voltage levels.

The values for frequency and rate of change of frequency (RoCoF) have been acquired with four identical mobile PMUs set on the highest reporting rate available (50 frames per second). The results considering a 2-hours time window with 10 minutes and 10 s details (based on the time aggregation intervals) are presented in Figure C.7.

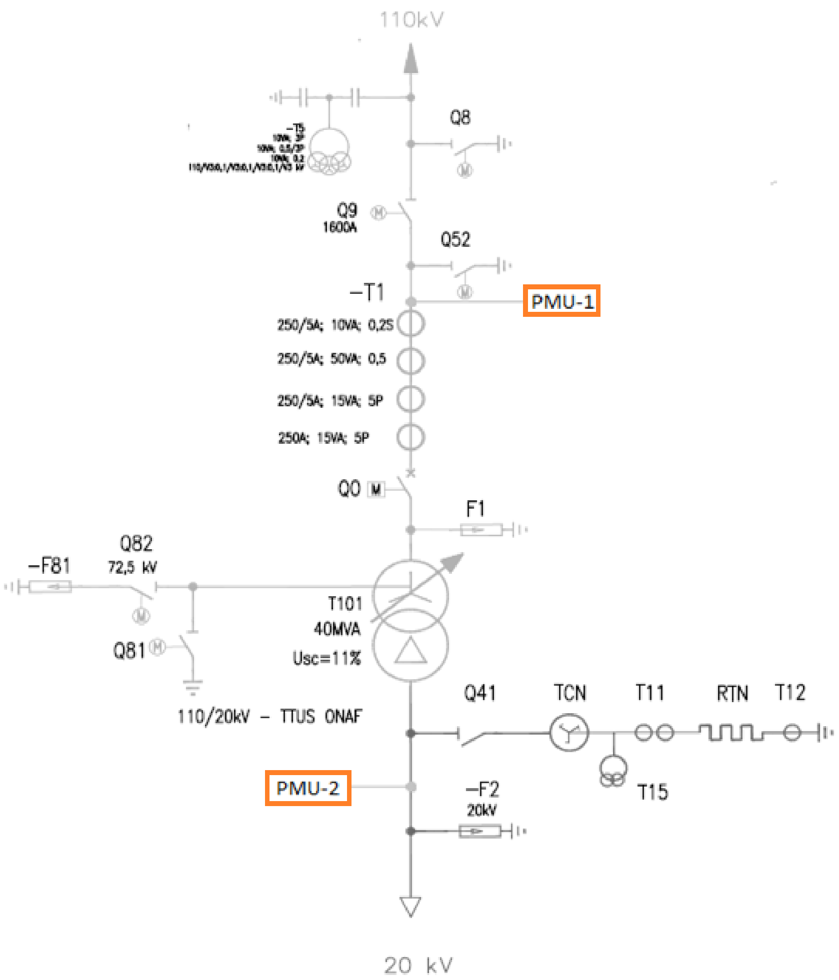


Figure C.4. Single phase diagram of power substation in Babadag, having two PMUs installed one at 110 kV and one at 20 kV [12].

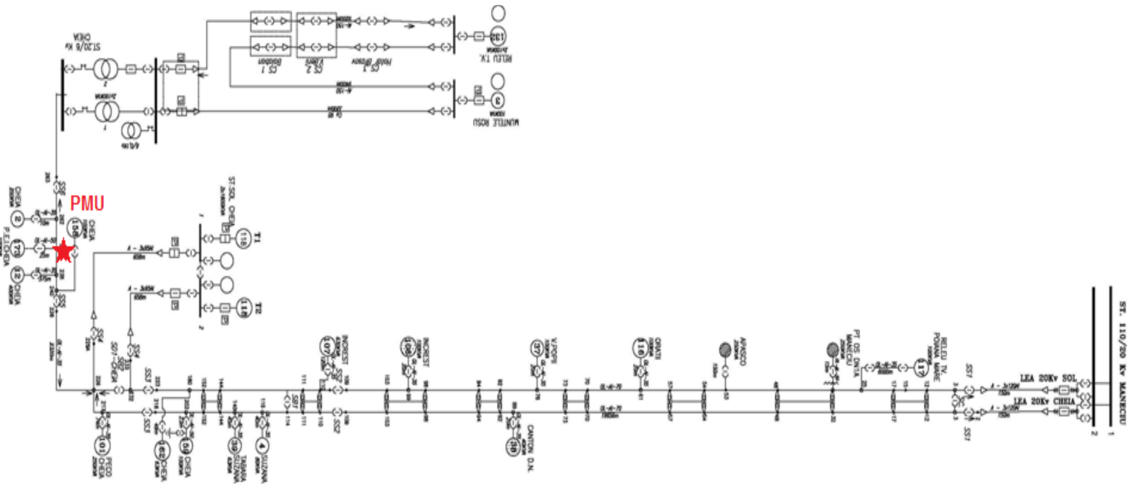


Figure C.5. Single line diagram of power substation in Cheia, having one PMU installed also at 0.4 kV. [12].

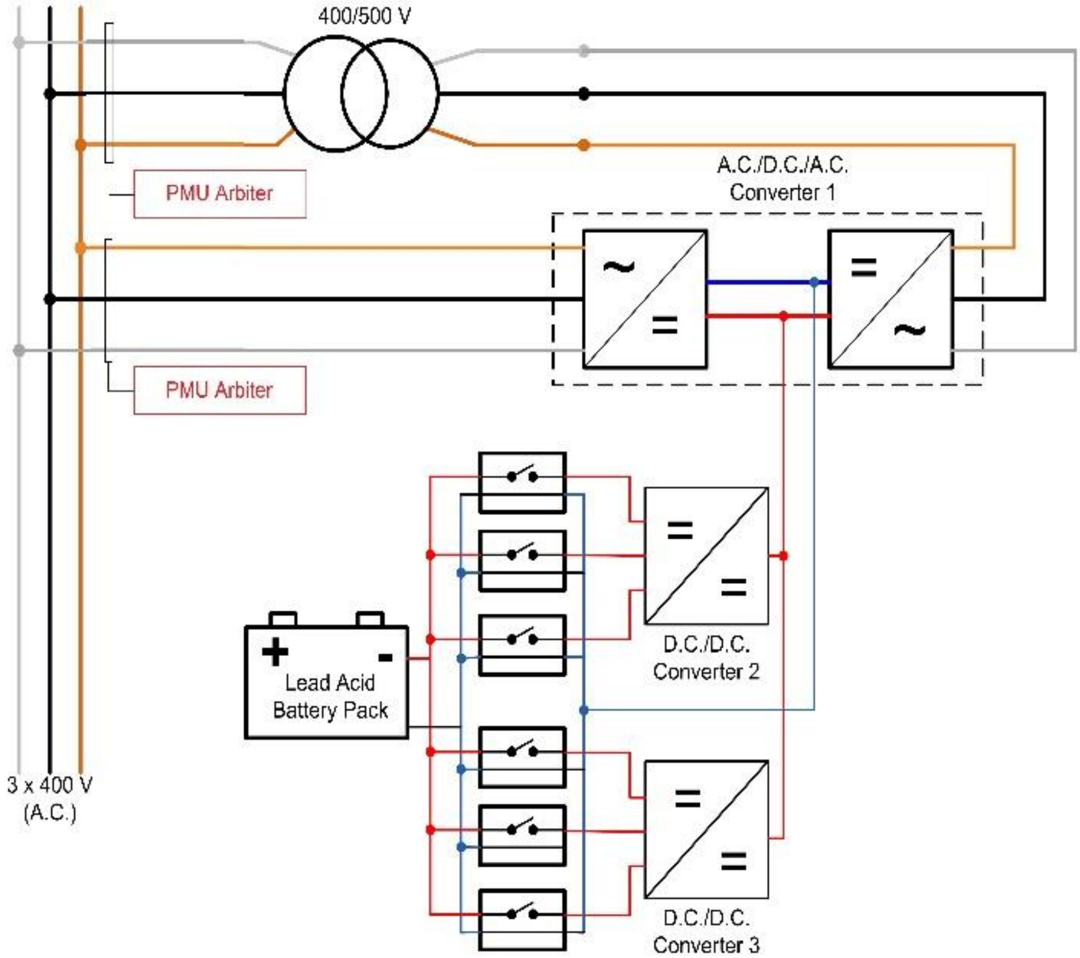


Figure C.6. PMU placement in Cheia [12].

The details for shorter measurement windows (10 seconds and 10 minutes) are presented in Figure C.7 to highlight the similar behaviour of frequency in all the considered cases (steady-state conditions). Although the values are not equal in all four nodes, the frequency variability pattern is the same. It is interesting to observe that this similar pattern excludes measurement noise from the potential sources of frequency variability in time. Also, one can see that frequency differences at some instants are one-order of magnitude larger than the measurement uncertainty, which supports the notion of “instantaneous, local” frequency.

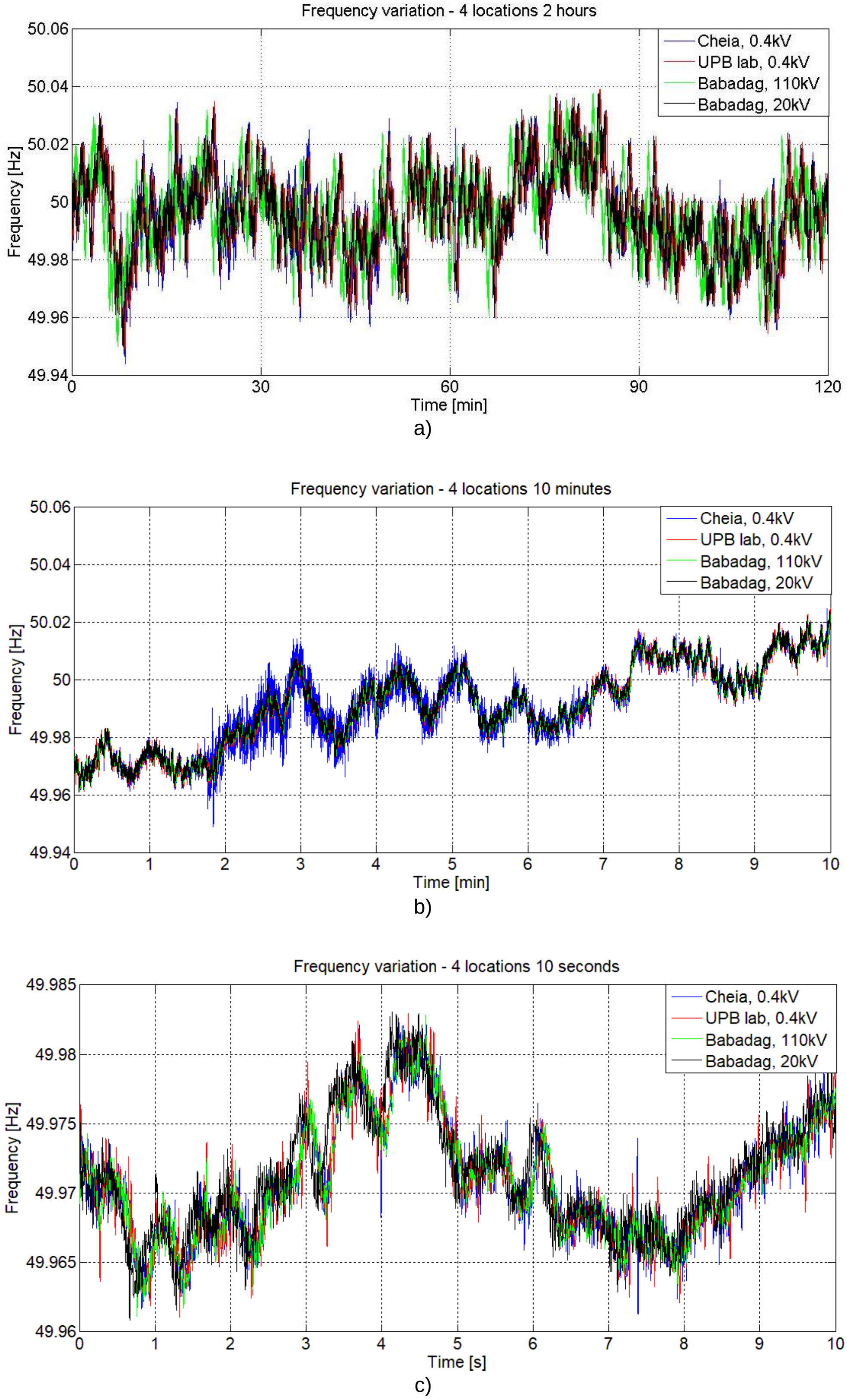


Figure C.7. Frequency in four locations: a) 2 hours; b) 10 minutes; c) 10 seconds.

C.4.2 Case 2. Frequency monitored at UPB by different equipment

In order to compare frequency measurements acquired with different reporting rates, we considered the three devices presented above: one PMU [7], one microPMU [9], one Unbundled Smart Meter using a ZMD405 meter as Smart Metrology Meter [21, 22], all connected to the same grid LV grid node (i.e. no additional instrument transformer in the measurement chain).

The comparison has been made in [23] as part of the RESERVE project for a measurement window including dynamic conditions, when the grid frequency had a maximum deviation in the range of a 100 mHz, corresponding to a sudden power unbalance in the Romanian network (part of the ENTSO-E operated power system) larger than 500 MW. Figures below show the evolution of each measurement for a 10 minutes window including the event.

Figure C.8 gives a general picture over 10 minutes, with the synchronized data from the frequency measurements reported by all three devices: microPMU, PMU and Unbundled Smart Meter (USM). Both microPMU and PMU detect the disturbance and associate it with higher frequency deviations than the meter does.

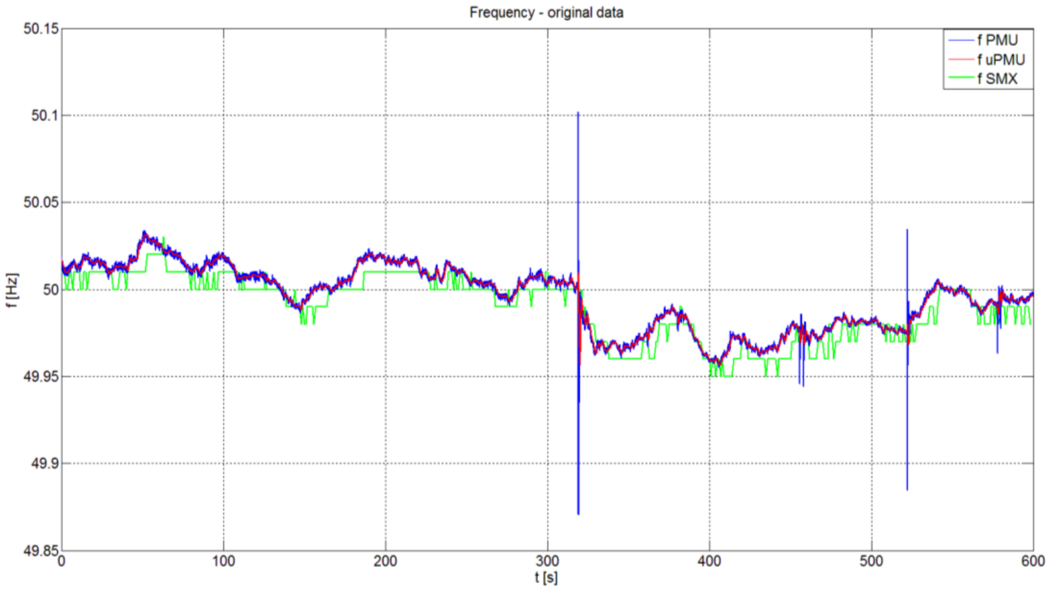


Figure C.8. Frequency variation on a 10 minutes monitoring window registered with PMU, microPMU and USM [23]

This is the result of the dynamic capabilities of the three devices, as reflected by the maximum available (and selected) reporting rate: PMU is set on 50 frames/s (successive data frames every 20 ms), microPMU is set on 100 frames/s (successive data frames every 10ms), and USM is set on 1 frame/s (successive data frames every 1 s).

Once can see that for steady state conditions, the high resolution for frequency measurement ensured by the USM allows good correlation with the more accurate devices (PMU-like). The average deviation of USM measurements, compared with those from the more sophisticated PMUs, is only half of its resolution, meaning 5 mHz, which is a good achievement for such a measurement equipment.

Figure C.9 gives a detail of the frequency variation during disturbance. The microPMU captures well the transitory period of the disturbance, when it shows oscillations associated with the dynamic behaviour of the power system. These oscillations are not captured well by the USM, due to its embedded aggregation algorithm.

However, this feature makes USM useful in processes with time-reaction of seconds or tenths of seconds, such as the frequency containment reserve (FCR), where technical minimum requirements, according to Article 154 and its Annex 5 of [24], ask for full FCR activation in 30 seconds and for a minimal accuracy of frequency measurement of 10 mHz, which are well covered by the 1 s reporting period for frequency and by the 5 mHz deviation as has been shown above.

Figure C.10 captures the frequency evolution during a 6 minutes monitoring for one second averaged microPMU and for USM frequency evolution. It shows comparatively the 1 s averaged data from microPMU and the USM reported values (1 frame/s). It can be seen that the USM measurements are well in line with the PMU measurements, capturing the pattern of the frequency evolution on a second-based sampling. The figure suggests again that the digital meter can be a reliable source of local frequency information for different applications where the time constant of the control loop (including decision making) is in the order of seconds, such as frequency containment reserve and other balancing mechanisms, especially in microgrids.

Table C.2. Comparative Characteristics of Different Measurement Equipment [23]

Description	PMU	Micro PMU	RTU/ BCU/ IED	Classic Energy meter	Unbundled Smart Meter
Synchronisation requirements	<1 μs	<1 μs	1 – 2 s	1 – 5 s	≤ 1 s
Reporting rate (typical) [frames/s]	50	100	1	1 – 0.2	> 1
Freq. resolution in steady state conditions [mHz]	<0.01	<0.01	10… 100	10..3 100	10
Accuracy	Spec.	Spec.	Not spec.	Not spec.	≈0.2%
Measurement capabilities	Dynamic state	Dynamic state	Steady state	Steady state	Steady state

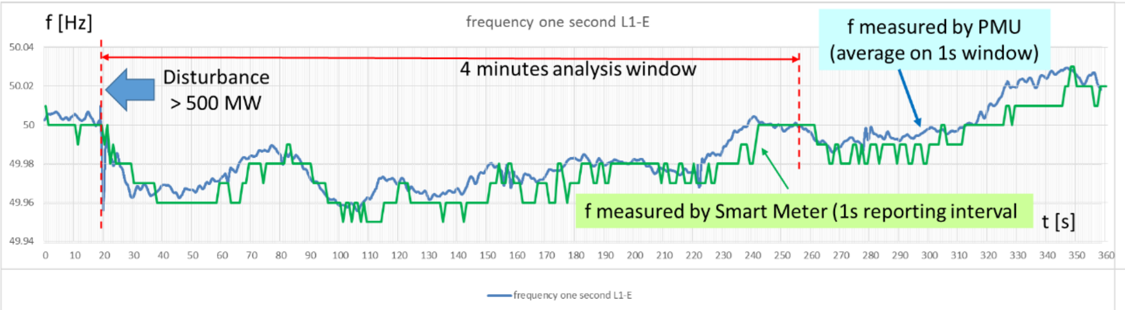


Figure C.9. Frequency during the power system disturbance: microPMU measurements (100 frames /s rate) and USM measurements [23].

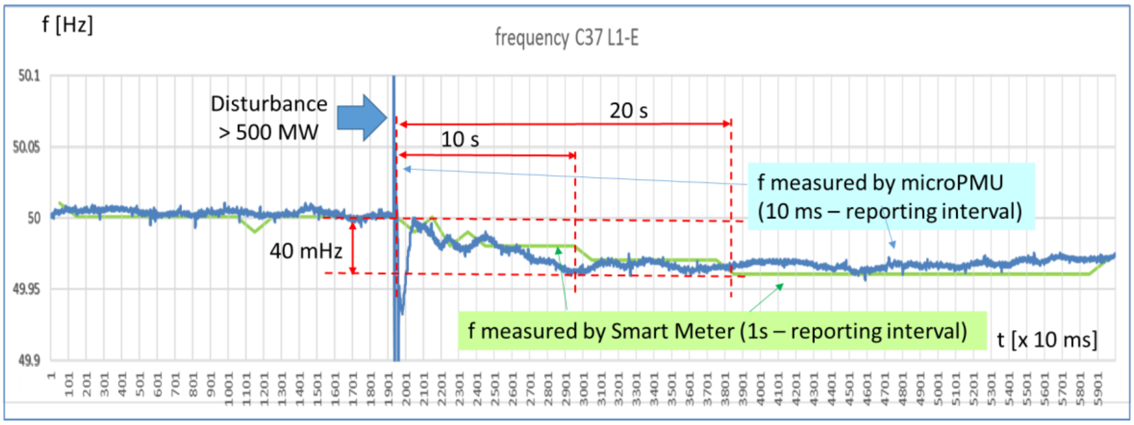


Figure C.10. Frequency during power system disturbance: microPMU data aggregated (asynchronous 100 points average) and USM data (original measurements) [23].

The biggest advantage of using the meter (instead of traditional synchronized measurement devices, PMU-like), beyond price affordability, is the fact that this is anyhow present at prosumer side for billing purposes and can be used also for such additional grid operation tasks.

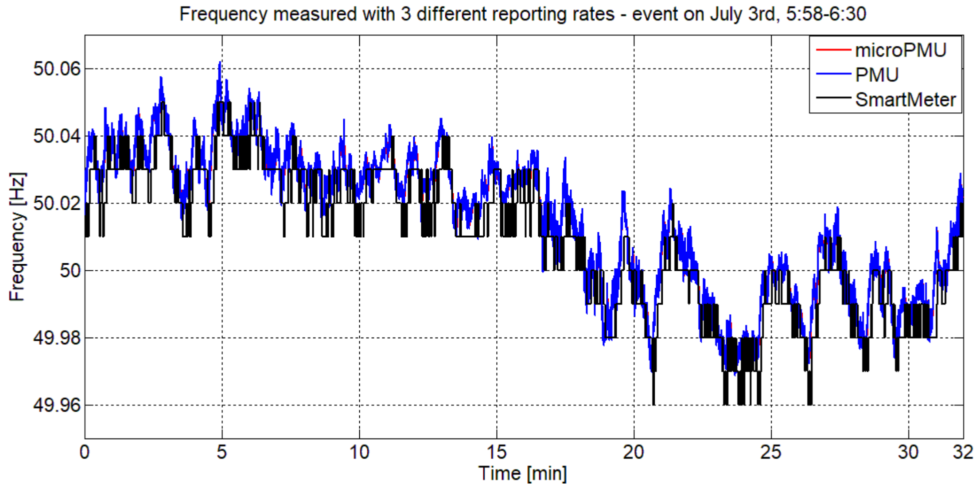
Figure C.10 presents more detailed frequency information derived from microPMU and PMU data reported during the disturbance, on a time window of 3 seconds. The microPMU has twice the reporting rate of the PMU and data are further mediated as to emulate lower rates: 1 frame/s. We also emulate the reporting rate of PMU (50 frames/s).

As the market trend is to have higher maximum reporting rates (100 frames/s or even larger), different types of application for all the acquired data implies the need for a dedicated, application dependent processing of information.

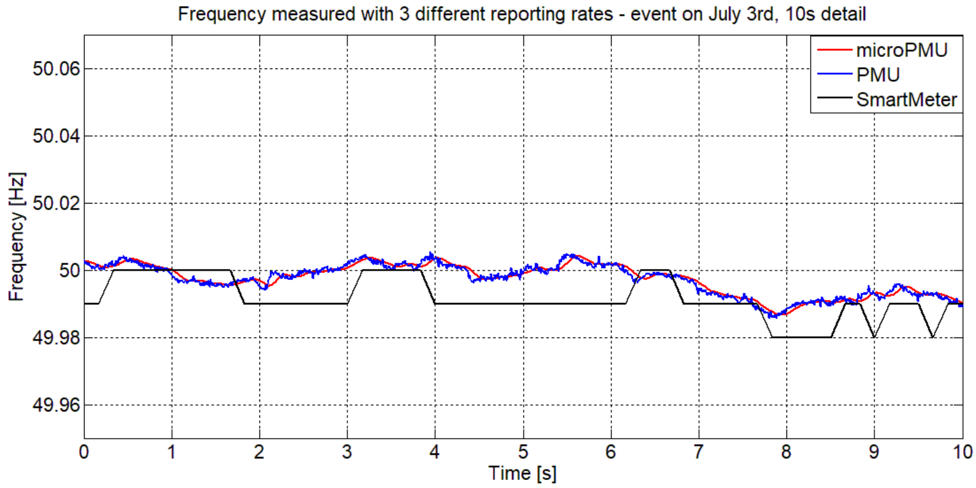
Using averaging algorithms for data aggregation to achieve data compatibility between data flows originally available with different reporting rates (and following different frequency estimation algorithms) is introducing additional filtering, which is associated with computational delay and information distortion (green line minimum value shows (Figure C.11) a delay of around 800 ms from the moment of disturbance), which may be badly accommodated in some SCADA applications.

The microPMU has a better dynamic behaviour during the initial transient period, with clear advantages in quasi-steady state control applications like dynamic state estimators.

The USM synchronization of 1 second was sufficiently good to pursue the frequency series measured with the PMU, thus showing that for grid services such as contributing at primary reserve with small resources the USM may be a viable candidate of the necessary measurements and actions.



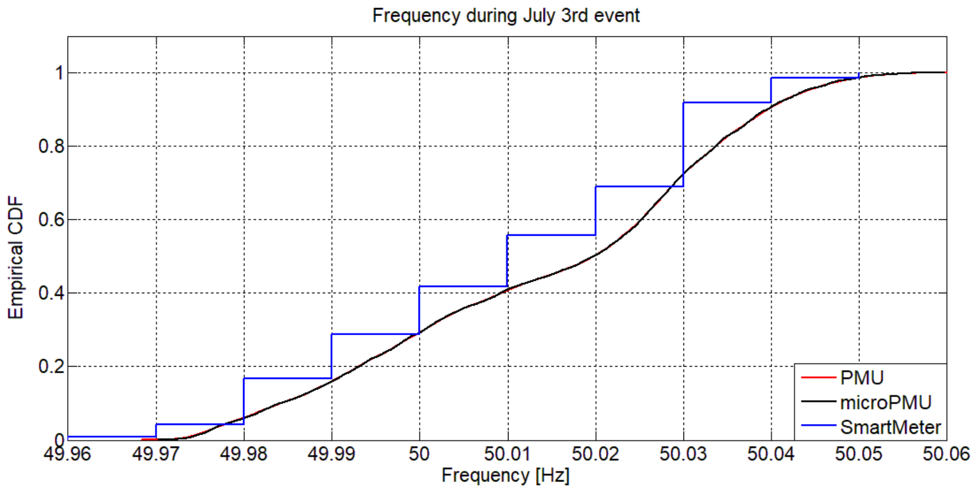
a)



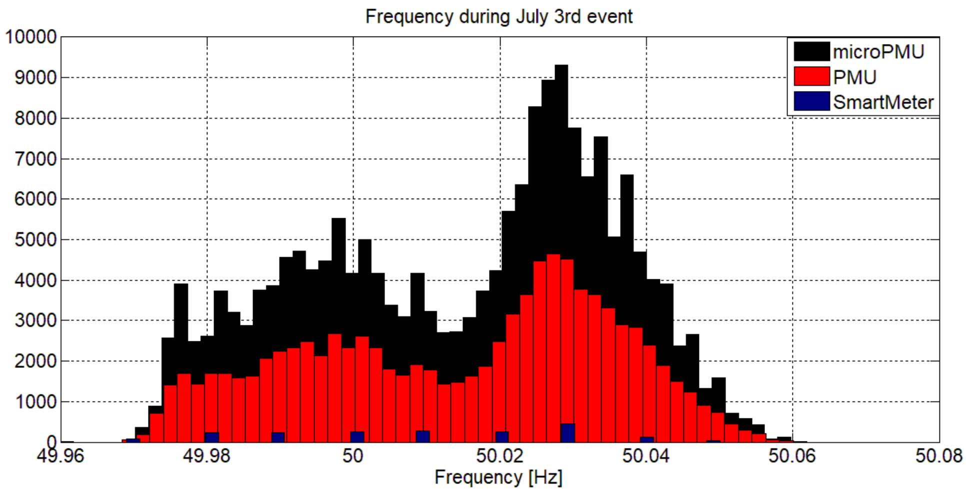
b)

Figure. C.11. Frequency measured with 3 different reporting rates (100 frames/s – micro PMU, 50 frames/s – Arbiter PMU, 1 frame/s – USM) – a) 30 minutes window; b) 10s window.

In figure C.11 another example of synchronous measurements with different equipment is shown to highlight the result presented in [23]. Just like in Figure C.8, the measured data with 3 reporting rates are compared. In Figure C.11a) the measurement information available with different reporting rates (and standard uncertainty) spans 30 minutes of frequency monitoring and captures an event in the national grid (Junly3rd, 5.58-6.30 am, local time). Figure C11.b) shows a 10 seconds detail. A confirmation of the fact that measurements data variability isdue to investigated power system phenomena (and its related dynamics during the event) is given in Figure C12. One can see that, despite the different reporting rates and accuracy, the three measurement devices deliver data with similar stochastic behaviour (both sets of histograms and CDFs are similar)



a)



b)

Figure C.12. Statistical behaviour for the measured data during the July 3rd event (measurement data presented in Figure C.11) – a) Empirical CDF; b) Histograms

Table C.3. Statistical data for measurements during the July 3rd presented event.

Equipment	Arbiter PMU	microPMU	Smart Meter with SMX
Minimum [Hz]	49.9684	49.9702	49.9600
Maximum [Hz]	50.0619	50.0590	50.0500
Mean [Hz]	50.0146	50.0146	50.0093
Median [Hz]	50.0198	50.0197	50.0100
Standard deviation [Hz]	0.0208	0.0208	0.0209

C.4.3 Case 3. Full day frequency variations analysis (July 3rd, 2017)

In this section uses data from the Arbiter PMU connected at LV in the UPB laboratory. Data is acquired for July 3rd, 2017. The objective of this section is to perform a quality analysis of the estimated (according to the PMU functionality) frequency and reported with highest available rate (no aggregation, 50 frames/s).

Figures C.13-C.16 present the frequency and RoCoF variation in time and the corresponding histograms. Despite the number of events that occurred during this particular day, the variation for both frequency and RoCoF have a normal distributionwith statistics presented in Figures C.17-C.18 and Table C.4.

It can be seen that, for 24h analysis window, both frequency and its derivative have a normal distribution with very low standard deviation; mean and median frequency values are very close to the nominal 50Hz frequency and zero Hz/s RoCoF.

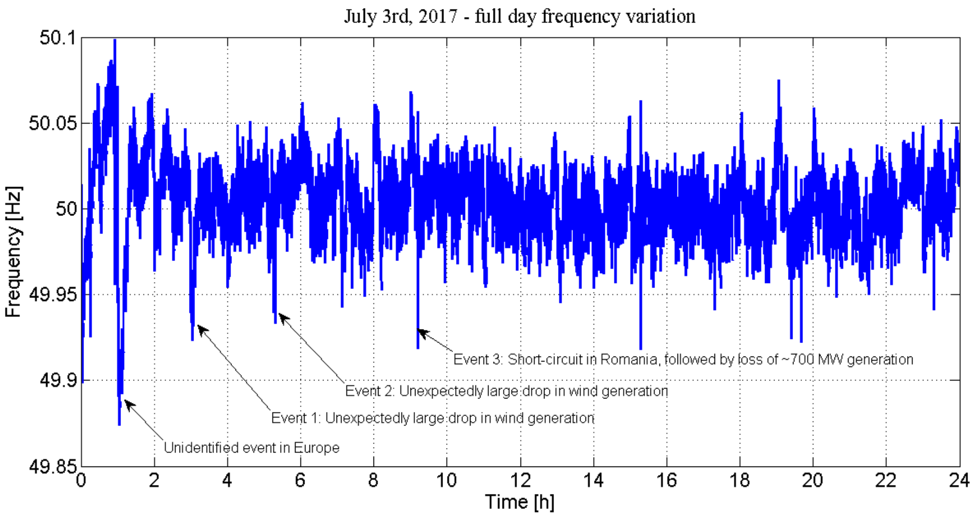


Figure C.13. Frequency variation. UPB (LV) laboratory, PMU data.

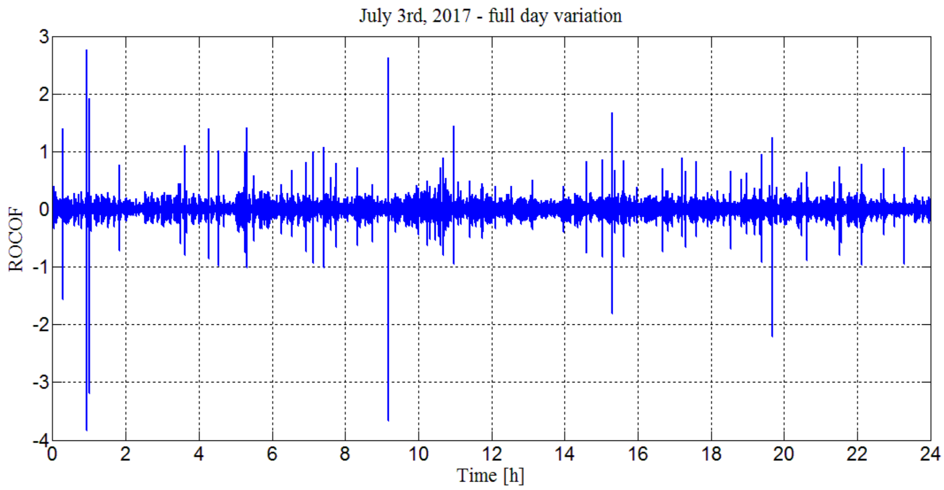


Figure C.14. RoCoF variation. UPB (LV) laboratory, PMU data

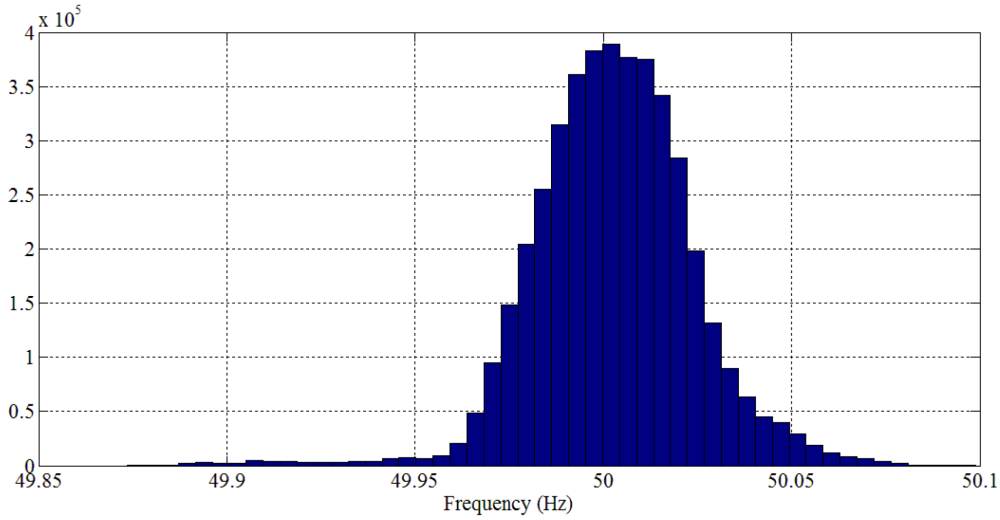


Figure C.15. Frequency distribution. UPB laboratory, PMU data.

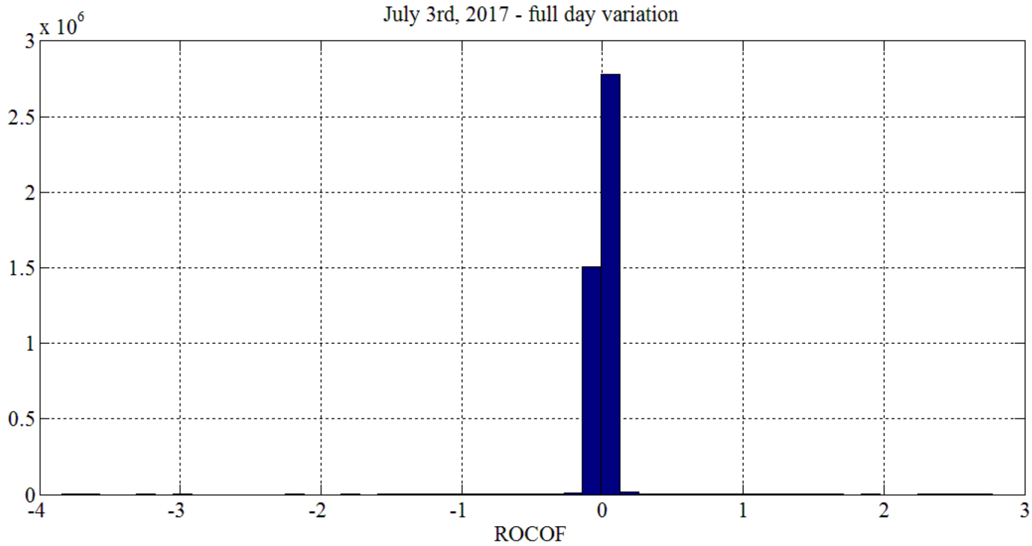


Figure C.16. Frequency distribution. UPB (LV) laboratory, PMU data

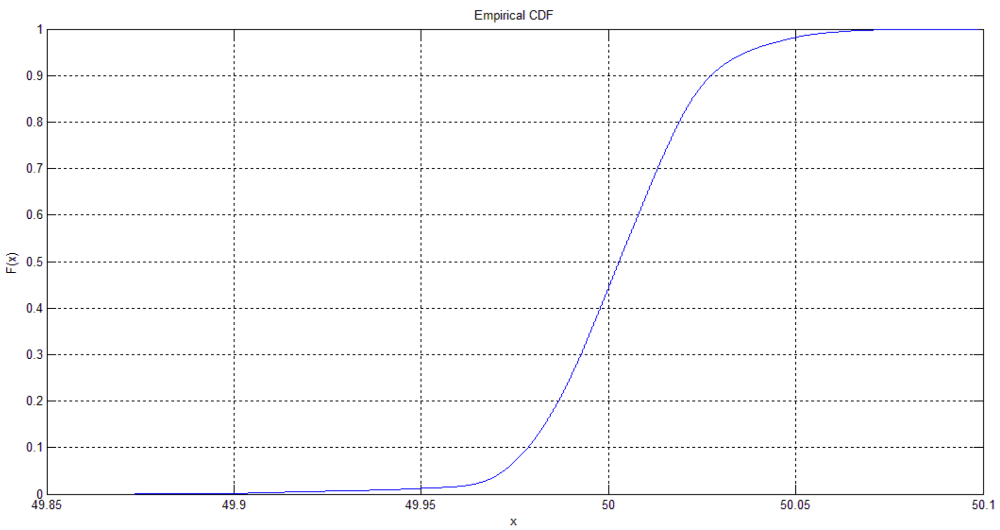


Figure C.17. Empirical; CDF for frequency data on July 3rd

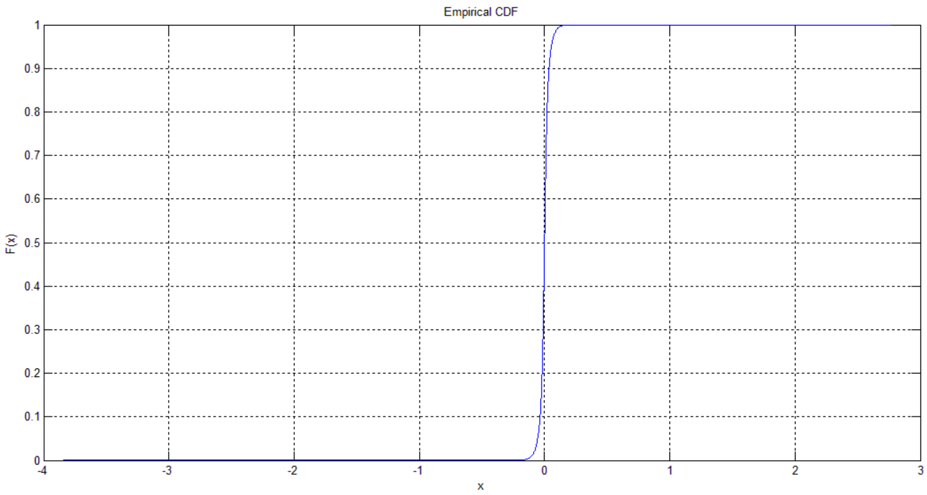


Figure C. 18. Empirical CFD for RoCoF on July 3rd

Table C.4. Statistical data for July 3rd – original data

Indicator [Hz]	Frequency [Hz]	RoCoF [Hz/s]
Minimum [Hz]	49.8736	-3.8409
Maximum [Hz]	50.0989	2.7672
Mean [Hz]	50.0029	7.1142e-08
Median [Hz]	50.0028	0
Standard deviation [Hz]	0.0212	0.0353

C.4.4 Case 4. Impact of data aggregation

In this section, the impact of data aggregation (as described in section C.2 – according to IEC61000-4-30 [17]) is presented. For this, the data used in Case 3 was aggregated using 3 levels (200 ms, 10 s and 10 minutes).

The graphical results together with the corresponding statistical data are presented below.

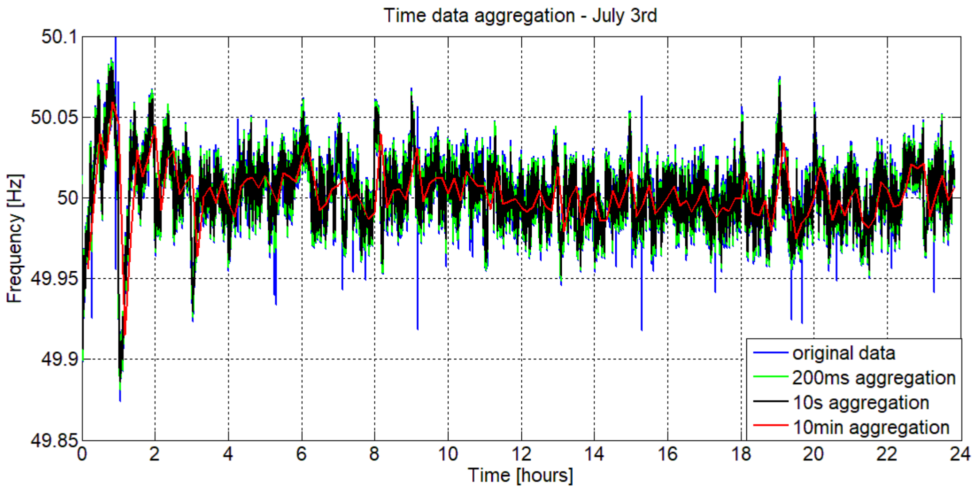


Figure C.19. Frequency variation during July 3rd, 2017 –data aggregation in time based on IEC 61000-4-30 [17].

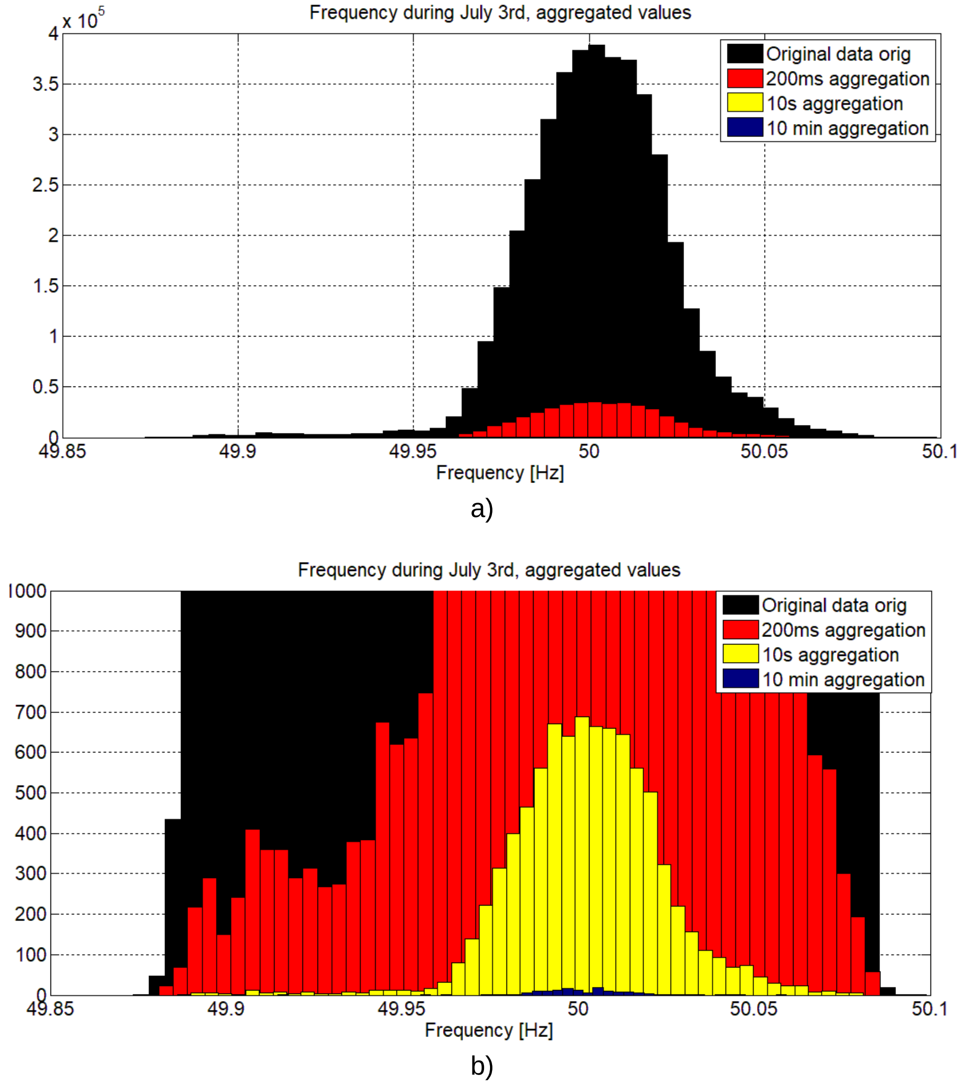


Figure C.20. Frequency histograms during July 3rd, 2017 –data aggregation in time, based on IEC 61000-4-30. – a) original view, b) detail

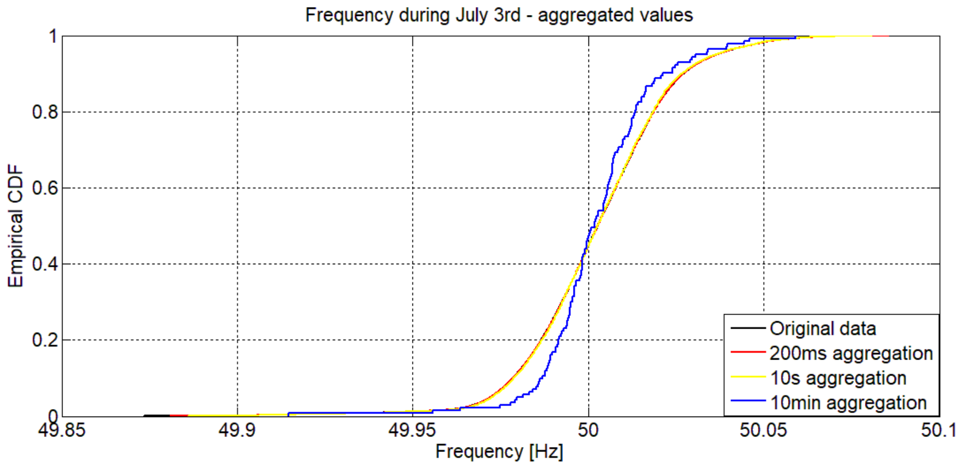


Figure C.21. Frequency CDF during July 3rd, 2017 –data aggregation in time based on IEC 61000-4-30.

It can be seen from Figures C.20 and C.21 and from Table C.7. that the main statistical behaviour of the data for the considered observation window is similar for the original data (50 frames/s) and the aggregated information, with the main exception of the 10min interval where the Empirical CDF and the histogram have different forms. Also, for the 10 min aggregated values, the minimum and maximum are significantly different when compared with the raw information from the PMUs. Figure C.19 highlights the similar variations for all levels of aggregation, with a higher difference for the 10 min interval.

Table C.5. Statistical data for the event on July 3rd – Impact of data aggregation

Equipment	Original data (20ms)	200 ms aggregation	10 s aggregation	10 min aggregation
Minimum [Hz]	49.8736	49.8808	49.8861	49.9147
Maximum [Hz]	50.0989	50.0856	50.0809	50.0591
Mean [Hz]	50.0027	50.0027	50.0027	50.0027
Median [Hz]	50.0026	50.0026	50.0026	50.0018
Standard deviation [Hz]	0.0212	0.0212	0.0209	0.0169