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WP 5

Increased Observability

Deliverable 5.2

Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes

22/12/2015

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This Intermediate Version of the D5.2 document outlines a methodology specifically created for developing and testing observables for the Web-of-Cells (WoC) concept.

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Executive summary

This Intermediate Version of the D5.2 document outlines the methodology adopted to define and test observables for the new power system control concept proposed, the so-called Web-of-Cells (WoC) concept. Starting from the future power system development (2035+) with a very high share of non-programmable RES mainly connected to the medium and low voltage power grid, it is straightforward to propose a rethinking of the current power system control strategy approach. In particular it is recommendable to overtake the conventional control schemes of the power system, based on voltage and frequency controls traditionally supplied by the largest power plants directly connected to the transmission system, and to replace those schemes with new ones, in order to take into account new distributed devices in operation, new ancillary resource requirements and new ancillary services suppliers. This implies a complicated process in terms of the definition of new control strategies and new technical requirements. In ELECTRA, in particular, instead of conventional frequency controls, more general balance types of control have been introduced, which, although including control of frequency itself, primarily involve control of active power exchanges. As for voltage controls, a two-stage structure, therefore simpler than the three-stage conventional one, is proposed. The adopted control approach comprises a generic physical description of the control challenge (balance control or voltage control), which is both technology independent and voltage level independent. So the generic definitions ”balance control” and ”voltage control” can be applied to all power system technologies, such as AC, DC, Superconducting, and to all voltage levels HV, MV, LV, et cetera. The envisaged approach requires the introduction of several new terms and definitions, which have been proposed in cooperation with mainly WP6 and also WP4. Some of these have been further developed from the previous Tasks, such as Control Time Scales (CTS), while the others are new, such as Control Topology Levels (CTL).

A selection of not regularly used Observables and Observable Algorithms (to compute observables form physical measurements) is made that serve the main Use Cases defined in ELECTRA Deliverable D3.1 "*Specification of Smart Grids high level functional architecture for frequency and voltage control*". These observable algorithms are to be further defined and tested within this Task 5.2 activity.

Preparing to the succeeding part of the Task 5.2 with implementations and testing, a specific part of work was dedicated to the further development of the Single Reference Power System (SRPS) started in Task 5.1. Among the major novelties is a demonstration of the SRPS for a simple test network.

The results indicate that the WoC concept together with the above mentioned methodology built on top of the well-known Use Case methodology are viable tools for determining observables for an electric power system supporting future energy systems.

Terminologies

Definitions

The ELECTRA IRP project has a commonly coordinated strategy related to the use of terms and definitions within the project. In WP4 “Interoperable Systems” an ELECTRA Glossary has been created, which collects and validates specific terms and definitions. The ELECTRA Glossary is available for the projects' participants in the file repository at www.electrairp.eu and is not included in the present document.

The ELECTRA Glossary is intended to be continuously updated during the project. In particular several new terms and definitions have been introduced or developed in WP5 “*Increased Observability*” for the scope of the ELECTRA project, or have a meaning different from the commonly used one. All these terms and definitions will be included in the Glossary.

The Table below shows a selection of the key definitions. Some of these were initially introduced in the preceding Task 5.1 and modified later on.

Table 1: Key definitions in the ELECTRA project

Term	Definition
Control Triple	A set consisting of {Control Aim, Observable, System Input Signal}, which is the basis of a control loop.
Control Quadruple	A Control Triple, extended with the element “Observable Algorithm”.
Control Aim	A concise statement describing the control purpose of a control loop.
Observable	A uniquely valued function of a number of measurable quantities in a physical system. An observable can either be a scalar or vector (“State Vector”) that is calculated from measured (observed) values in the present or past.
Transition Time	Time for system response or system control loops to complete the transition from a stationary system state to the next stationary state, after a switching event occurs within a power system.
Control Time Scale	A characteristic Transition Time at which a control loop operates. In this document the following Control Time Scales (CTS) are used: • CTS_0: System response • CTS_1: Primary Level • CTS_2: Secondary Level • CTS_3: Tertiary Level
System Input Signal	A (scalar or vector) signal that is input to the power system, in order to change the value of an observable.
Observable algorithm	A detailed description of (or reference to) a specific set of operations that convert measurable values into an observable.
Control Topology Level	A characteristic Topology Level at which a control loop operates. Here the following Control Topology Levels (CTLs) are used: • CTL_0: Physical (single) Device Level • CTL_1: Flexible (aggregate) Resource Level • CTL_2: Cell level • CTL_3: Inter-cell level (For a more detailed definition of the Control Topology Levels see, [9] chapter 21.5. "Working procedure for selecting control functions for Use

Term	Definition
	Cases")
Balance Control	Control loops that serve to keep the power balance between generation and loads.
Voltage Control	Control loops that ensure that voltage at each node keeps within operational limits, in a stable, secure and reliable way. Voltage control includes the needed control of power flow in all cables and lines in the network, with methods depending on the used power system technologies (AC, DC).
N.B: The definitions of "Balance Control" & "Voltage Control" comprise a generic physical description of the control challenge, which is both technology independent and voltage level independent. So these generic definitions can be applied to all power system technologies. such as AC, DC, Super conduction, and to all voltage levels HV, MV, LV, et cetera.	
Cell	A group of interconnected loads, concentrated generation plants and/or distributed energy resources, and storage units within well-defined grid boundaries corresponding to a physical portion of the grid and corresponding to a confined geographical area.

Abbreviations

ALF	Accuracy Limit Factor
AVR	Automatic Voltage Regulator
BRC	Balance Restoration Control
BRP	Balance Responsible Party
BSC	Balance Steering Control
CTL	Control Topology Level
CTS	Control Time Scale
CVD	Capacitive Voltage Divider
CVT	Capacitor Voltage Transformers
D	Deliverable
DER	Distributed Energy Resources
DFT	Discrete Fourier Transform
DSO	Distribution System Operator
ENOB	Effective Number Of Bits
ESS	Energy Storage System
FCC	Frequency Containment Control
GPS	Global Positioning System
IEC	International Electrotechnical Committee
IFSC	Institute Of Santa Catarina

IRP	Integrated Research Program
IRPC	Inertia Response Power Control
LSB	Least Significant Bit
MS	Milestones
NPFC	Network Power Frequency Characteristic
OPF	Optimal Power Flow
PCC	Point of Common Coupling
PLC	Power Line Carrier
PMU	Phasor Measurement Unit
PPVC	Post-Primary Voltage Control
PSS	Power System Stabilizer
PVC	Primary Voltage Control
R	Internal Report
RES	Renewable Energy Sources
RMS	Root-Mean-Square
ROCOF	Rate-Of-Change-Of-Frequency
SCADA	Supervisory Control And Data Acquisition
SE	State Estimator
SF	Safety Factor
SMES	Superconducting Magnetic Energy Storage Systems
SNR	Signal-to-Noise Ratio
SOC	State Of Charge (Of Energy Storage System)
SRPS	Single Reference Power System
SVC	Static Var Compensator
TSO	Transmission System Operator
UC	Use Case
WOC	Web-of-Cells

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1 Introduction

The European Union has defined several ambitious climate and energy targets including the well-known 20-20-20 ones [5] and the 2050 EU Energy Roadmap [20].

Achieving these goals will require a major change from conventional generation (fossil fuelled power plants) to Renewable Energy Sources (RES) on different scales, ranging from large offshore wind farms to small-scale domestic PVs for instance, and feeding into networks on various voltage levels.

Great challenges are anticipated for the secure operation of the future power system (2035+), in connection with the foreseen transition from centralised to decentralised generation. Implementation of novel control strategies will enhance flexibility of the power system enabling it to accommodate a broad spectrum of decentralised and intermittent renewable energy sources in order to provide sustainable and economical supply of electricity. Some descriptions of energy mix future scenarios in Europe which are compatible with this view are provided in [4].

Some of the above mentioned changes can already be noticed in countries like Denmark, where wind power generation already provides more than 35% (39% in 2014 [7]) of annual electricity consumption and more than 90,000 PV units are feeding into networks on different voltage levels. These changes create several challenges for DSOs and TSOs, making it difficult and costly to operate the system in a reliable and secure manner.

1.1 WP5 “Increased Observability”

Safe accommodation of larger and larger amounts of intermittent and distributed generation into the network and reliable operation of the network itself require a gradual evolution of the network structure and in particular improvement of its control, monitoring and observing. Adequate observability of the system operating state is a requirement for a reliable and secure supply of electricity.

Monitoring of the electricity network in the past was limited by the lack of capable ICT technologies, in combination with the fact that operation of the conventional vertical "downfall" power system did not necessarily require excessive monitoring, especially in the distribution network. Development of ICTs and integration of these as a new layer into the electricity network, also known as smart grids, is diminishing the technical limitations and improving the power system observability.

As an input, control strategies for future grid operation will require a whole new class of system observables in order to suffice the required awareness needed, which will be much higher than at present due to the massive presence of decentralized and stochastic power sources.

The main objective of WP5 "Increased Observability" is therefore to develop and implement adequate concepts and methods for sufficiently observing the state of the future power system along the following three axes:

- Pan-European
- Vertically integrated
- Local (Horizontal/ Distributed)

It is foreseen that during the ELECTRA 3rd year activity, the suggested observability schemes will be defined and harmonised among the partners and then implemented in lab platforms programmable in advanced languages (Matlab, SciLab or similar); the results will be transferred to WP7.

The present report is the intermediate version (M18) of the second deliverable in WP5 (D5.2) and presents the methodology and first results of Task T5.2 "Observables for Distributed Local Control Schemes".

1.2 Relation to other WPs

The text below is in accordance with the similar chapter in Deliverable D6.1, "*Functional specification of the control functions for the control of flexibility across the different control boundaries*".

In order to develop coordinated control functions in T6.2, the work is based on close collaboration between:

- WP4 - Fully Interoperable Systems
- WP5 - Increased Observability
- WP6 - Control Schemes for the use of flexibility
- WP7 - Integration and Lab Testing for Proof of Concept

To simplify understanding of the roles of different WPs, Figure 1 shows the abstraction of the control system and how different work packages interface with each other and with the individual parts of the control system.

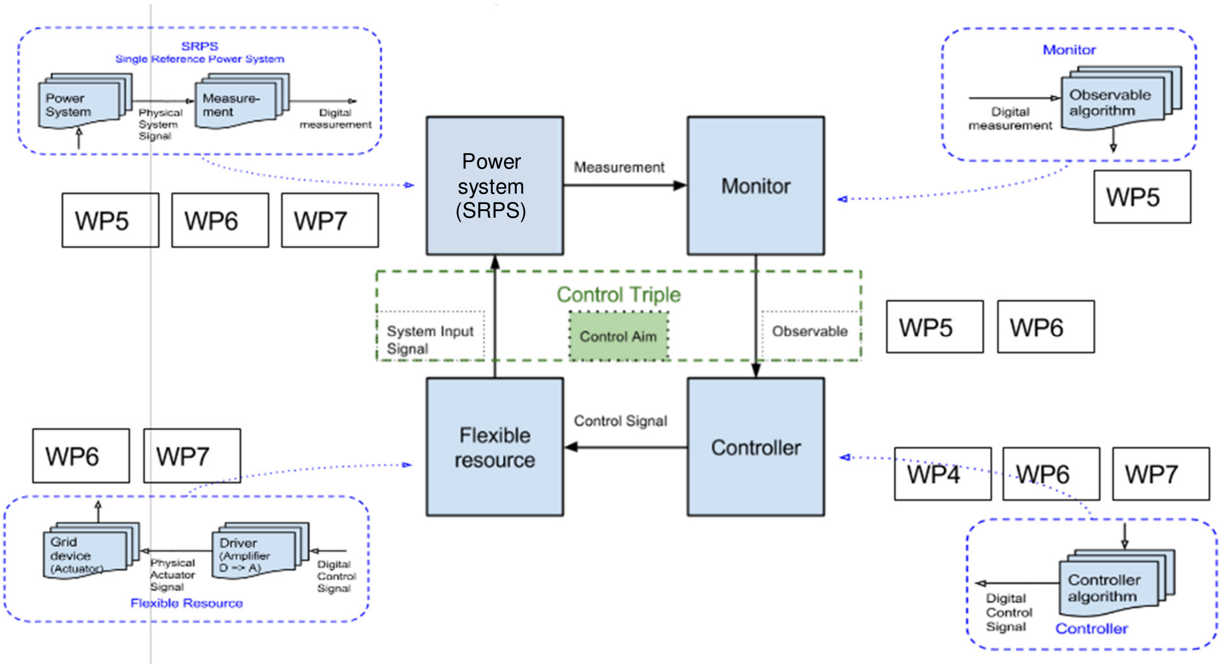

Figure 1: Black Box Control System and interfaces between WP4, WP5, WP6, and WP7.

In this abstraction, the control system consists of four "black boxes": Power System [3], Monitor, Controller, and Flexible Resource. SRPS stands for "Single Reference Power System", which is a simple formal way to describe the power system under study and which will be dealt with in details in Chapter 2.

In the core of the control system is the so called Control Triple consisting of Control Aim, Observable, and System Input Signal. The development of control systems for the future power system is based on Use Cases. For a certain Use Case or certain coordinated control action or control aim, it is possible to create a simple picture which consists of the four aforementioned "black box" components describing the control system or control loop. The control function needs real measurements and status information of the grid (see the Power System box), both from the network and its connected (flexible) components. The digitized measurements (voltage, current, temperature measurement etc.) are basic measurement signals, all as a function of time. The Monitor processes the measured signal and gives an Observable which is input to the Controller. The Controller compares the Observable to a certain set point value according to the particular control aim. The Controller supplies the control signal to the Flexible Resources. The Flexible Resources provide the System Input Signal to the Power System; that signal, of course, depends on the Control Signal received from the Controller.

The outer corners of Figure 1 describe how the different WPs considered relate to the control system parts, i.e. to the four black boxes. In particular, the upper right corner of Figure 1 refers to WP5, because the monitored signals are processed to observables which are defined by WP5. WP5 and WP6 make use of Control Triples, as these provide a physical basis for the control loop in the abstraction. In the right lower corner of Figure 1, the Controller is relevant to WP4, WP6, and WP7, because control algorithms need to be developed and tested. Flexible Resources have an interface to WP6 and WP7 in left lower corner of Figure 1, because they may include real grid devices (actuators) and drivers (amplifiers) which change the digitalized control signal to a physical analogue actuator signal. In the left upper corner of Figure 1, the Power System is shown to be comprised of two elements: the power grid and the measurements. The latter change physical measured signals to digitized signals for the Monitor. This interfaces to WP5 with regard to measurements and observables, and to WP6 and WP7 with regard to module and laboratory testing of control loops using a particular grid model.

1.3 Assumptions and limitations of the study

The overall objective of the ELECTRA project is to develop new control solutions for 2035 and beyond. Expectations and scenarios for a future with such a relatively distant time horizon will inevitably contain a substantial amount of uncertainty. Even though the work package has tried to mitigate the overall uncertainty relating to the publically available roadmaps for the near future it is still necessary to make several assumptions in order to handle these future uncertainties. The following main assumptions have been made:

- **Technology and cost limitations are not fully considered.** Considering the rapid development during recent years in technologies such as communications and computation, and the long time horizon that is being considered within the project, the Task decided not to constrain itself to the present technological limitations. Similarly, the present high costs for the most recent and less spread technologies are not considered as an actual limitation, because technological advancement normally leads to significant cost reductions.
- **Potential conflicts between different control schemes are here not considered.** In fact, these conflicts are planned to be addressed more specifically in WP6 "Controllable Flexibility" according to the project's DOW. Therefore the present Task does not omit any control schemes due to potential conflicts between these.

1.4 ELECTRA approach to power system control: main definitions

1.4.1 Web-of-Cells concept - solving local problems locally

In the future grid, a scenario shift is expected from large central synchronous generators at transmission level to smaller, and usually intermittent (such as PV panels, wind turbines, etc.), production units at distribution level, which cannot participate directly in central balancing by the TSO and do not provide inertial response power for instantaneous balancing. Furthermore, coincident non-intermittent loads like EV battery charging stations and heat pumps may cause temporary overloads in LV and MV substations and lines.

One of the key pillars in the ELECTRA vision is that the European 2020 goals are not achievable without radical changes in the existing power system control paradigm. During the course of the project a novel architecture concept for the future power system has been suggested. The "Web-of-Cells" concept was coined, which is described more specifically in Deliverable D3.1 [2] and will be further elaborated in subsequent Tasks in WP4. Following this concept, the future European power grid will be decomposed into a new structure - the Web-of-Cells, where the cells are defined as follows:

- A cell is a group of interconnected loads, concentrated generation plants and/or distributed energy resources, and storage units within well-defined grid boundaries corresponding to a physical portion of the grid and corresponding to a confined geographical area.
- A cell is not a microgrid. In ELECTRA, microgrids are defined as being able to operate in grid-connected as well as "island" mode [6]. Being able to operate in island mode is not a requirement of a cell.
- A cell is in 'normal state' when in real-time operation:
    - it is able to follow the scheduled consumption/generation set-point so that the voltage, frequency and power flows are within the operational security limits;
    - it is able to activate sufficient flexible ancillary resources (active and reactive power reserves).
- Cells have adequate monitoring infrastructure installed, as well as local reserves capacity, enabling them to resolve voltage and cell balancing problems locally.

Since the concept of WoC is under development within ELECTRA, the above description refers to the latest agreed definition (see [2]). Modification and clarification of several definitions is pending in the moment of writing. A schematic depiction is given in the next Figure 2.

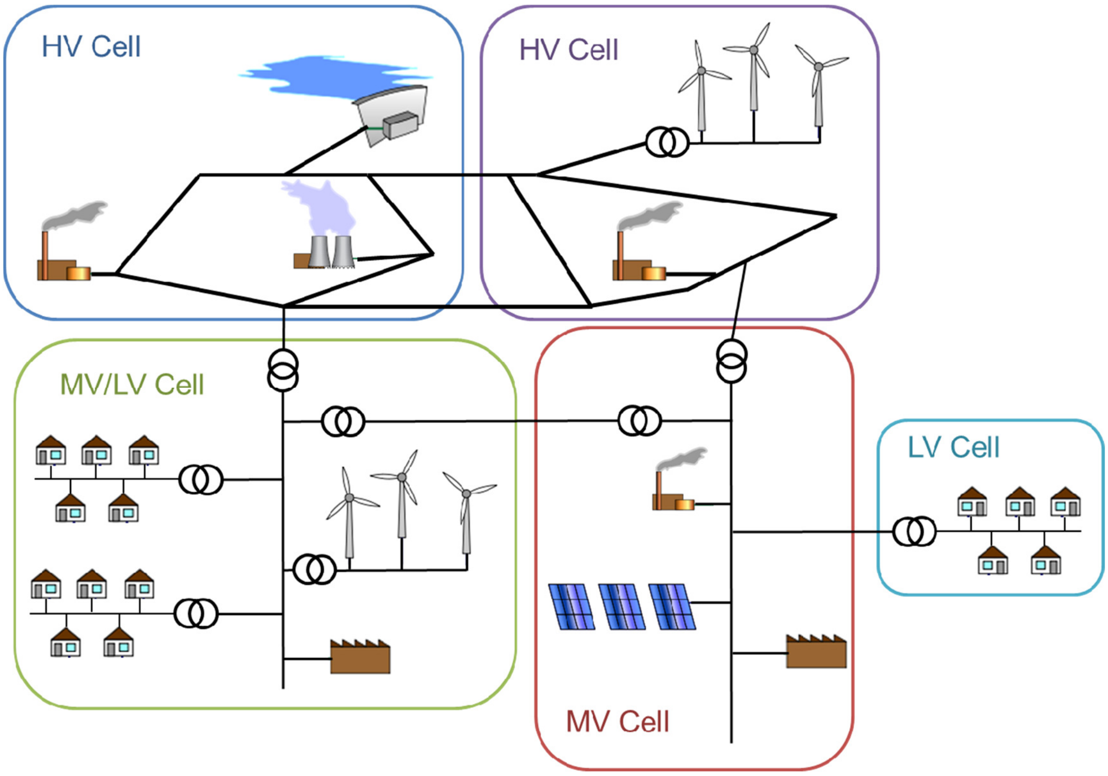

Figure 2: Schematic example of the proposed "Web-of-Cells" architecture. Source: [2]

The ELECTRA vision in brief applies a cell-based control concept for solving local control problems locally, i.e. at cell level, as far as possible. Considering that many partly predictable decentralised resources will dominate the future grid, the cell will serve as a collective system capable of effective distributed control and facilitating efficient use of the decentralised resources.

Even though this cell based approach is expected to be more simple and effective due to its proximity to the source of the problem, compared to the conventional centralised architecture, it has the consequence that global reserves activation optimization is disregarded. Examples of such system-wide optimizations are:

- Economic optimization, by replacing restoration reserves by more cost-effective ones.
- Imbalance netting, system-wide reduction of opposite sign activations.

Disregarding the global optimisation may require coordinative function across cells. This issue is evaluated by the project in the moment of writing.

1.4.2 Balance and Voltage Control

Within the scope of ELECTRA, the terms "Balance Control" and "Voltage Control" are adopted for the two main control functionalities needed:

Balance Control

Control loops that serve to keep the power balance between generation and loads.

Voltage Control

Control loops that ensure that voltage at each node keeps within operational limits, in a stable, secure and reliable way. Voltage control includes the needed control of power flow *in all cables and lines in the network, with methods depending on the used power system technologies (AC, DC).*

The definitions of "Balance Control" & "Voltage Control" comprise a generic physical description of the control challenge, which is both technology independent and voltage level independent. So these generic definitions can be applied to all power system technologies, such as AC, DC, Super conduction, and to all voltage levels, HV, MV, LV, et cetera.

Besides, the Balance Control definition aims to be more general than the usual frequency control definition, since it is focused on active power balance, which includes but does not restrict to the control of frequency itself (frequency, of course, can be defined for AC systems only). In other words, correct and stable frequency is an index of power balance (control), but it is not the only variable involved in it.

Voltage Control for AC networks, in particular, mainly involves ensuring the dispatch of the reactive power according to the requirements of the network and of the customers. In this respect, it can be considered as an extension to all voltage levels of the control actions currently taken on reactive power in the very high / high voltage transmission networks. However, on distribution networks, it can also include control actions on active power injection/absorption. Besides, in case of Distributed Generation connected to the MV or LV grid, controlling frequency and voltage may not be independent tasks, but the two controls may have to be coordinated (in fact, acting on active power to control frequency may affect voltage as well). This is a new functionality to be required, for instance, to inverters connecting DG.

1.4.3 Use Cases

Both for balance control and for voltage control, control specifications have been formulated with reference to a set of different objectives to be met in order to ensure power balance, correct power transfer, local and overall system stability and security. These objectives, with the related control actions, are organized into a set of Use Cases. The main Use Cases in the ELECTRA project have been defined in Deliverable D3.1 [2]. They will be dealt with in details in this deliverable; anyway, they are collected together in the next table for convenience.

Table 2: Main Use Cases in ELECTRA

Control Type	Use Case abbreviation	Use Case name	Control aims
Balance Control	B1.IRPC	B1-Inertia Response Power Control	**Objective 1**: Reacts to frequency changes over time (frequency transient plus dynamic response) **Objective 2**: Observes and regulates in real time the available amount of inertia within a Cell
	B2.FCC	B2-Frequency Containment Control	**Objective 1**: Reacts to deviations of the frequency value so as to contain any change and stabilise frequency to a steady-state value **Objective 2:** Observes and regulates in real time the Network Power Frequency Characteristic (NPFC) for the WoC or NPFC within a Cell
	B3.BRC	B3-Balance Restoration Control	Reacts to absolute frequency deviations in conjunction with the tie line power flow deviations from the scheduled interchanges so as to restore both quantities to their initial values

Control Type	Use Case abbreviation	Use Case name	Control aims
	B4.BSC	B4-Balance Steering Control	Regulates power balance within a Cell (proactively or reactively) in order to replace BRC reserves or mitigate potential imbalances in a cost effective manner
Voltage Control	T1.PVC	T1-Primary Voltage Control	**Objective 1**: Reacts in case of voltage deviations detected in any nods of a Cells as a consequence of a severe disturbance **Objective 2**: observes, monitors and regulates the voltage levels deviations in real-time in the grid nodes within the Cells
	T2.PPVC	T2-Post-Primary Voltage Control	**Objective 1**: Restores the voltage levels in the grid nodes to the set-point values within in a safe band Simultaneously, it optimizes the reactive power flows in the system. **Objective 2**: regulates the voltages in the nodes in case of generation-demand imbalances

1.5 Deliverable contents

The present document covers the following activities performed in Task 5.2:

- Clarification of the scope of Local Control schemes
- More specific stepwise definition of the methodological approach for the whole Task
- Identification of control aims, based on a set of Use Cases (UCs) from D3.1 [2]
- Identification of the needed Control Triples, with use and extension of the Control Triples' Survey from D5.1 [3]
- Determination of methods for specific observables

The material in this document is thus organized:

- Task methodology:
  - general methodology (definitions, working procedure, ...);
  - methodological aspects relevant to both Balance and Voltage Control;
  - Balance Control;
  - Voltage Control;
- Selection of observables for the main use cases: separately for balance control and for voltage control:
  - followed methodology;
  - first choices of observables and related simulation results.

The final version of D5.2, scheduled for completion in M33, is intended to update this intermediate version, in particular to:

- Report on basic control loop simulation, including reliability analyses, based on chosen Control Triples
- Implement the suggested observability schemes into modules to be implementable in WP7 "Integration and Lab Testing for Proof of Concept".

2 Methodology

2.1 General Methodology

2.1.1 Working procedure for selecting observables and their algorithms

The procedure followed for selecting observables and their control aims is shown schematically in the next picture:

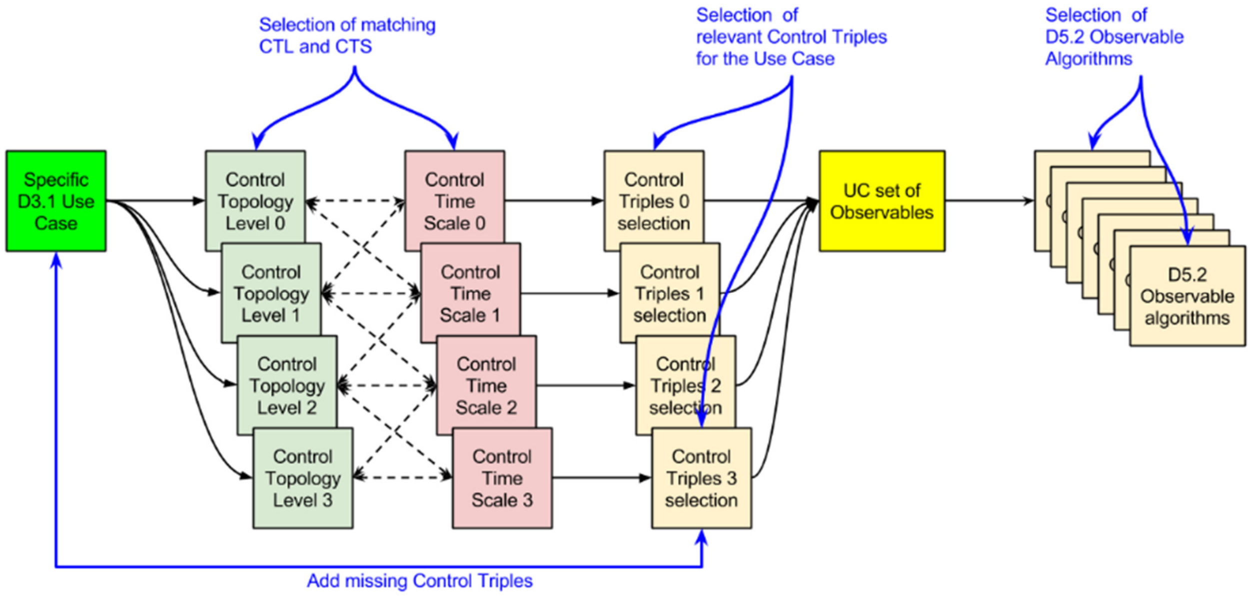

Figure 3: Working procedure for selecting observables and their algorithms.

- The starting point is a specific main Use Case from D3.1 [2]
- For each main Use Case, all possible combinations of Control Topology Levels (CTL) and Control Time Scales (CTS) are listed and kept up-to-date in an online automated spreadsheet, for all WP5 partners to use and update concurrently.
    - This is done in the online spreadsheet "Use Cases-Control Triples" Tab:"UC Sub-Cases" [18]
- For each combination, relevant Control Triples are chosen that can be selected in a cell from an automatically generated drop-down list of previously defined values.
    - These Control Triples are defined in the extension of the D5.1 [3] online spreadsheet 20150119-Observables inventory survey.
        - The working procedure of that spreadsheet is described in D5.1. [3]. The first tab of the spreadsheet explains the procedure and contains a link to an online webinar where this is demonstrated (see [10] for the Webinar).
    - Non-existent cases are marked "no case", and automatically the row in question of the spreadsheet turns grey to indicate this to the user.
- From the final list, the set of the selected observables used and their algorithms are filtered out by a pivot table, which is an automated user friendly function.
- Finally, observables are selected that need to be clarified or defined further as they are not commonly used in practice yet. These will be tested in simulation and/or implemented in hardware modules in the remainder of Task 5.2.

2.1.2 Black Box control loop interface to other WPs

Although the Task mainly concerned with the specification of control loops is T6.2 "Development of robust coordination functions for multiple controllers across different control boundaries", within the frame of T5.2 it is essential that we should define some basic but fully functional control loops that on a later stage will be used as a basis for simulation purposes and validation of the selected control triples.

These control loops are expected to facilitate the clear and common understanding in the consortium of the requirements that led to the selection of the proposed control triples.

In order to have an easy and standardised interface and to facilitate the information transfer to the other WPs in ELECTRA, a Black Box depiction of a control loop interface has been agreed among WP4, WP5 and WP6, as shown in the next figure.

In particular the WP3 "*Scenarios and case studies for future power system operation*" and WP4 "*Fully Interoperable Systems*", may benefit from the dimensionless signal definitions adopted in the general Black Box depiction in the next figure.

From the perspective of the present Deliverable D5.2, the focus is on the observables and their algorithms, while the description below is given in order to put this into context.

The correct operation of the control loop is based on the Control Triple introduced in deliverable D5.1 [3], and depicted in the center of Figure 4 as {Control Aim, Observable, System Input Signal}.

- The "Monitor" block contains the implementation of an Observable Algorithm,(such an algorithm translates a scalar or vector measured quantity into an observable).
- The "Controller" block contains the implementation of a control algorithm which starts from the observable value and works out an action to be taken by the "Flexible Resource" in order to fulfill the "Control Aim".
- The "Flexible Resource" represents the needed physical equipment that is able to change the state of the power grid (based on the action order, i.e. the control signal, received from the "Controller").
- The "Power System (SRPS)" block represents the power grid (model) used.

As for the last item, in order to have a uniform approach towards models, simulations and tests in all WPs, the data necessary to describe the selected power grids and to implement their models are collected under a common format called the "Single Reference Power System" (SRPS), which will be dealt with in Chapter 2.

The signals "Measurement", "Observable" and "Control signal" are chosen such that they have no physical dimension, and are merely digital signals. All signals can be vectors of values processed simultaneously.

The Monitor processes a Measurement into an Observable, which in turn is processed by a Controller to deliver a Control Signal as an input to a Flexible Resource.

Of course, the physical System Input Signal provided by the Flexible Resource to the power system must be such that it can change the observable value. Otherwise one may end up with a broken control loop that cannot meet its Control Aim.

The Flexible Resource and its physical "System Input Signal" to the "Single Reference Power System" may only appear at the lowest level of a cascaded control where the grid is directly controlled. At the top level the Control Signal is a direct input to the SRPS, which already contains lower level controls that take the Control Signal as an input.

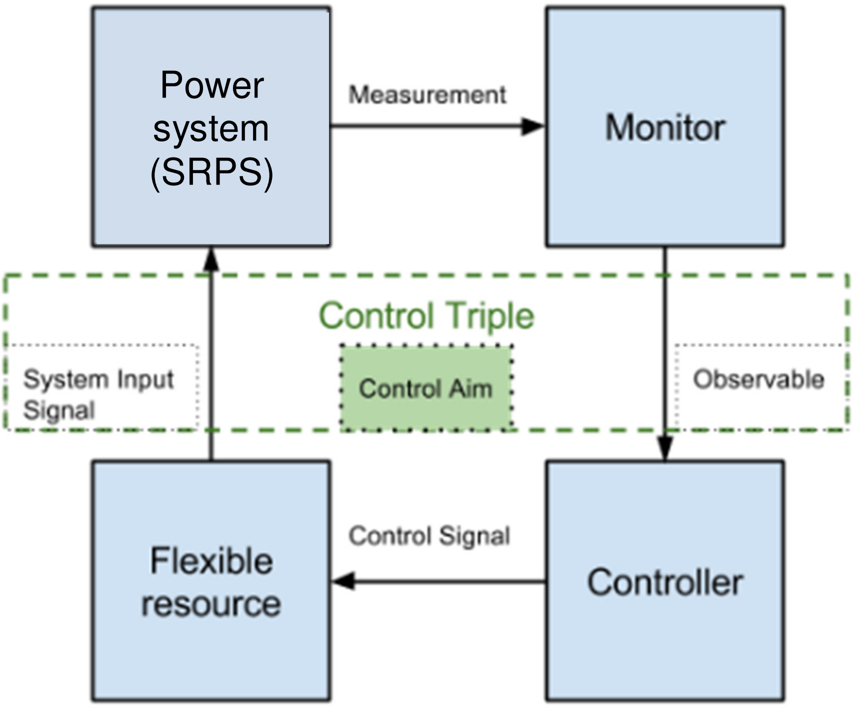

Figure 4: General Control Loop with Black Box Functions.

2.1.3 Control relations in the Web-of-Cells power system

In the next Figure, a partial view is shown of the Control relations in the WoC power system.

At the top we have an Energy Market, which hands out set-points for e.g. cell tie-line power (see the BRC use case) and cell inertia (see the IRPC use case), that lie within Secure Operation Intervals. This is done once per market time interval, e.g. every 15 minutes.

The Power System is monitored in order for an Emergency Control to take necessary actions, in order to prevent blackouts, when the Power System goes into alert condition.

In case of an emergency, the central set-points for the secure Operation Intervals are dictated directly by the Emergency Control, thereby overriding the Energy Market. As soon as normal operation is restored, the control is handed back to the Energy Market again.

The Power System consists of Cells that each have a Cell Monitoring system, which serves both the Cell Control and the Power System Monitoring. The Power System Monitoring is an overall fast Monitoring function that in case of major system events or disruptions can serve Emergency Control in the Web-of-Cells in order to restore normal operation.

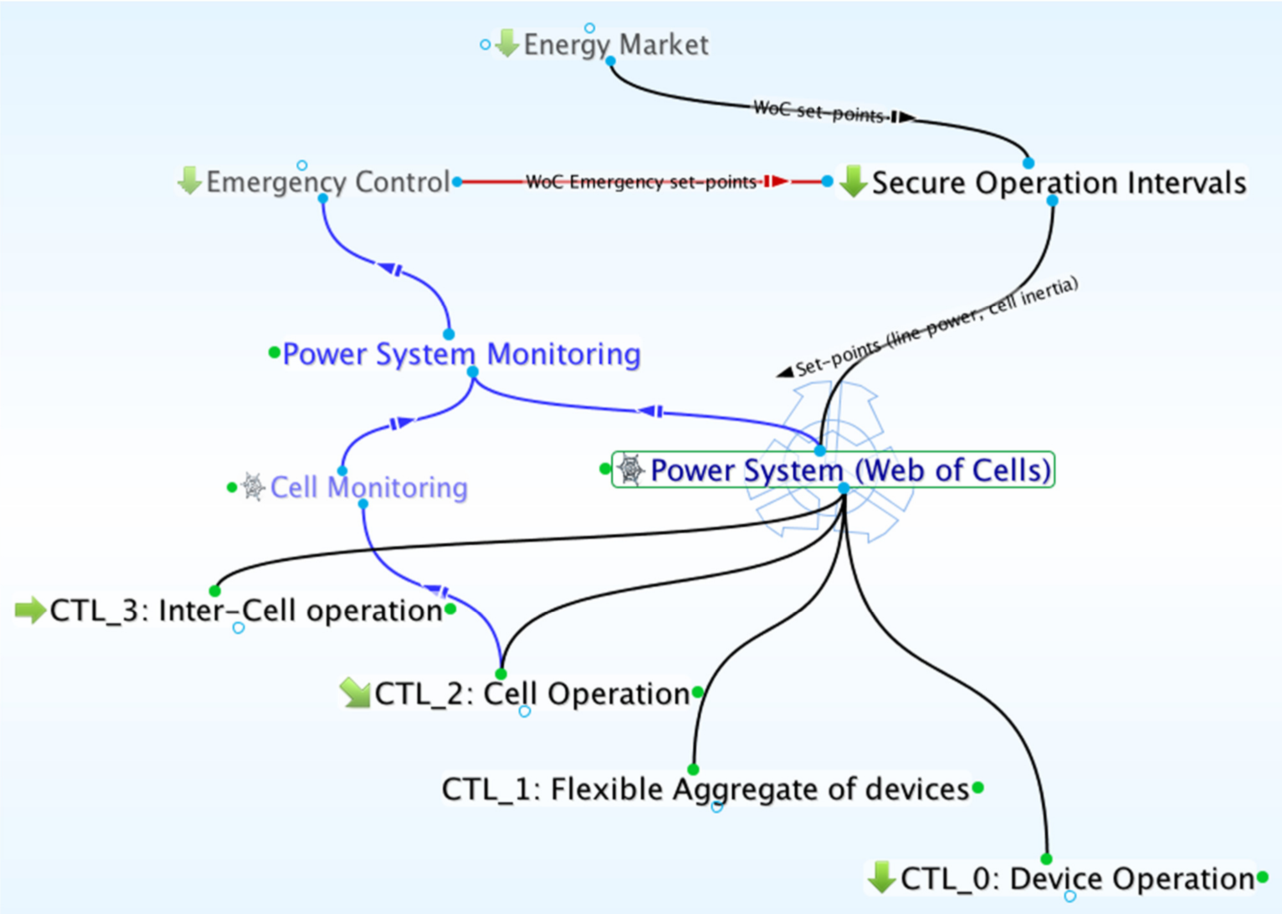

Figure 5: Control relations in the Web-of-Cells power system

Cells are controlled autonomously by Control Functions comprising four Control Topology Levels:

- CTL0: single physical device level
- CTL1: aggregated flexible resource level
- CTL2: cell level
- CTL3: inter-cell level

In general this implies that controls at different CTLs form Cascaded Control schemes, where a control loop at a certain CTL gives the setpoint for the control loop at a lower CTL.

A Control Topology Level operates in a certain Control Time Scale (not shown in the Figure), which depends on the specific Control Function it serves:

- CTS0: system response (5 s)
- CTS1: primary level (30 s)
- CTS2: secondary level (120 s)
- CTS3: tertiary level (900 s)

These "Control Time Scales" have been defined earlier in [3] D5.1, Chapter "4.4.3 Control Levels", under the name "Control Levels". In the present Deliverable, the name has been adapted in order not to get confused with the notion "Control Topology Levels".

A control scheme at a certain Control Time Scale is defined by a Control Triple. This is a set consisting of {Control Aim, Observable, System Input Signal}, which is the basis of a control loop.

2.2 Methodology - Balance and Voltage Control

2.2.1 Methodology - Sub-Task 5.2.3.Basic control loop simulation, based on chosen Control Triples

2.2.1.1 Choice of simulation software

A power system simulation tool is intended to model the behaviour of different grids with different characteristics, topologies or voltage levels. A particular software package usually comprises several types of elements to build those network models, such as lines, transformers, electrical machines, loads, distributed energy resources (DERs), etc., but it also provides the environment for the definition of user-written models according to some compatible programming language.

The needs of every client depending on his/her business are very different. Due to this, it is not simple to establish a comparison between diverse commercial software, since any of them was designed with different purposes. The selection and the employment of one software is based on multiple factors related to the calculation capabilities, the simplicity of use, the number and types of available models or the friendliness of the interface layout.

A well-known open issue about (power system) simulation software tools is data portability between different simulation platforms. This is because a common exchange data format has not been adopted. This issue is also something to be overcome in the ELECTRA project in order to allow the transference of the results between different WPs.

With the purpose of ensuring the interoperability, a survey has been conducted in order to know about the simulation software capabilities of the partners involved in ELECTRA, and to get an idea about the potential power simulation tools available to be used within the project. Results are compiled in section 3.1.1.1.

2.2.1.2 Methodology - Choice of SRPS

As it was explained in D5.1 [3], the Single Reference Power System (SRPS) is a concept currently under development in ELECTRA and suitable for efficient power system modelling. The SRPS tries to avoid contradicting information in reporting formats and software implementations (incompatible translations between different software implementations of the same physical power system). A set of common definitions and rules for power system description (specifically for the Web-of-Cells control architecture) will be established to enable effective partner cooperation and avoid redundancies and ambiguities.

The SRPS will serve to build comparable simulation models of a certain power system in different simulation languages. The SRPS will only be made once for a certain power system model, and will facilitate the implementation in any specific software used by each partner and the results comparison between them.

For the proper choice of the SRPS an analysis of present test grid models is paramount. Therefore, a second survey has been distributed among the partners to collect examples of grid models developed by private or public institutions (in the framework of other research projects) known by the ELECTRA consortium. Information about commonly used grid models (here called “test grids”) repositories from significant institutions was also included.

From all the collected information, a summary table was done to provide an easy view. The main characteristics of the analysed power system models include:

- Data privacy (public, private, restricted)

- Number of nodes
- Voltage levels (LV/MV/HV)
- Type of studies that can be accomplished with the available data (steady-state studies and/or transient regime studies)
- Availability of distributed energy resources models in the grids and their type (Wind, PV, Storage, EV...)
- Data format

A total amount of 14 single test grids and 5 repositories were considered as containing valuable information for the future construction of the ELECTRA SRPS. From the bulk data received, some test grids or repositories were discarded from the outset: the data privacy precluded its employment within the project, they could not be converted to a common SRPS format or there was a lack of essential information in that test grid to be used according to the ELECTRA goals.

In the chapter 10. Annex: Summary of SRPS candidates the main characteristics about the single test grids or repositories assembled from the survey are summarized and presented by using a common template.

2.2.1.3 Define small test grid in SRPS

In ELECTRA the simulation work has been distributed in the following way: basic control loops for balance and Voltage Control will be modelled and simulated in WP5 “Increased Observability” and more complex control systems will be developed in WP6 “Control schemes for the use of flexibility” for controller design and control conflict analysis.

Within the WP5 scope, a small test grid and its description as an SRPS is presented below as an example (just for illustrative purpose of the concept). The selection of the final SRPSs to be used for the different control Use Cases, at different levels (from local to pan-European), is ongoing.

The simple network proposed, and shown in Figure 6, is the following: a synchronous machine is connected through an overhead line to a 10kV/400V transformer; on the LV side of the transformer two cables are used for connection to two loads and a PV array.

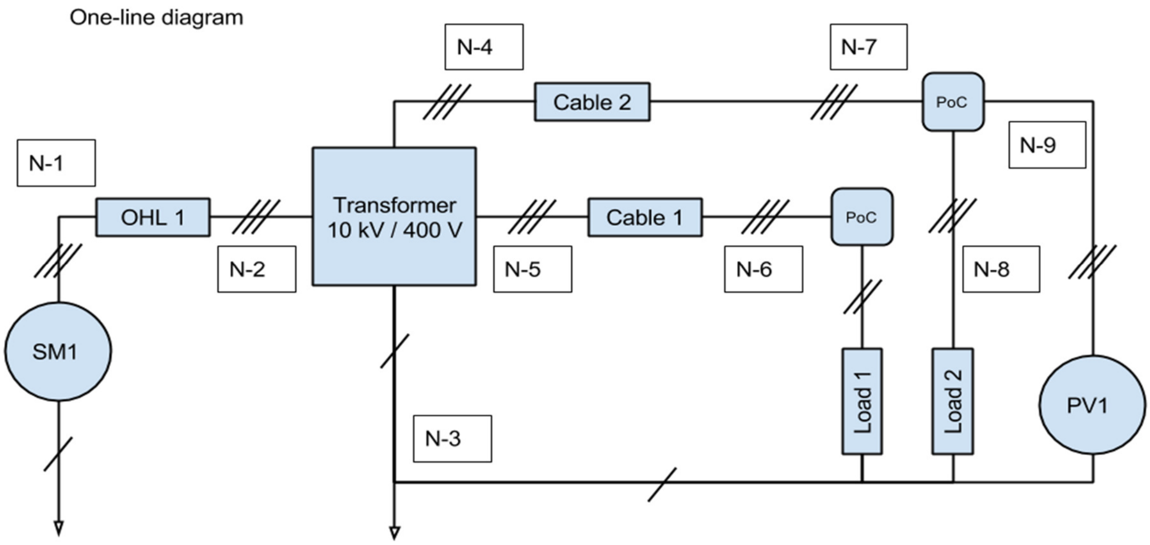

Figure 6: Example grid for SRPS description

Following the SRPS concept, the system above must be described as simply as possible (with the minimum set of parameters for each component), in an unambiguous way, employing a black box approach for the components, and avoiding information that is not interesting for the user.

The information needed for the SRPS description is organised by means of the spreadsheet shown below, where the topology, terminal types and main characteristics of the network elements are considered (just for illustration of the concept).

All numbers in SI base units			Physical description of grid element as black box			
	Grid Element		Terminals			
SRPS Record number	Label	Grid Element Type	Terminal Type-1	Terminal Type-2	Terminal Type-3	Terminal Type-4
1	SM-1	Synchronous Machine	abc	0		
2	OHL-1	Overhead Line	abc	abc		
3	T-1	Transformer	abc	abc	abc	0
4	Cable-1	Cable	abc	abc		
5	Cable-2	Cable	abc	abc		
6	Load-1	Load	abc	0		
7	Load-2	Load	abc	0		
8	PV-1	PV Array	abc	0		

Figure 7: Example grid for SRPS - Black Box Terminal parameters

All numbers in SI base units						
	Grid Element		Node connections of terminals			
SRPS Record number	Label	Grid Element Type	Terminal node-1	Terminal node-2	Terminal node-3	Terminal node-4
1	SM-1	Synchronous Machine	N-1	N-3		
2	OHL-1	Overhead Line	N-1	N-2		
3	T-1	Transformer	N-2	N-4	N-5	N-3
4	Cable-1	Cable	N-5	N-6		
5	Cable-2	Cable	N-4	N-7		
6	Load-1	Load	N-6	N-3		
7	Load-2	Load	N-8	N-3		
8	PV-1	PV Array	N-9	N-3		

Figure 8: Example grid for SRPS - Node connections of black box terminals

All numbers in SI base units			Properties of black box terminals			
		Grid Element	Nominal power flow of terminals [W]			
SRPS Record number	Label	Grid Element Type	Nominal power [W + j*VAr]-1	Nominal power [W + j*VAr]-1	Nominal power [W + j*VAr]-1	Nominal power [W + j*VAr]-1
1	SM-1	Synchronous Machine	1.00E+05	0.00E+00		
2	OHL-1	Overhead Line	1.00E+04	1.00E+04		
3	T-1	Transformer	1.00E+04	1.00E+04	1.00E+04	0.00E+00
4	Cable-1	Cable	1.00E+04	1.00E+04		
5	Cable-2	Cable	1.00E+04	1.00E+04		
6	Load-1	Load	5.00E+03	0.00E+00		
7	Load-2	Load	5.00E+03	0.00E+00		
8	PV-1	PV Array	3.00E+03	0.00E+00		

Figure 9: Example grid for SRPS - Nominal powers of black box terminals

All numbers in SI base units		Grid Element	Nominal Voltages of terminals [V]			
SRPS Record number	Label	Grid Element Type	Nominal Voltage [V+j*V]-1	Nominal Voltage [V+j*V]-1	Nominal Voltage [V+j*V]-1	Nominal Voltage [V+j*V]-1
1	SM-1	Synchronous Machine	1.00E+04	0.00E+00		
2	OHL-1	Overhead Line	1.00E+04	1.00E+04		
3	T-1	Transformer	1.00E+04	400	400	0
4	Cable-1	Cable	400	4.00E+02		
5	Cable-2	Cable	400	4.00E+02		
6	Load-1	Load	400	0.00E+00		
7	Load-2	Load	400	0.00E+00		
8	PV-1	PV Array	400	0.00E+00		

Figure 10: Example grid for SRPS - Nominal voltages of terminals

2.2.2 Methodology - Sub-Task 5.2.4. Hardware test

From the set of Use Cases (UCs) from D3.1 [2], test cases for the simulations have to be developed. For each test case, the grid, load profiles, control triples, algorithms, component models and all other input parameters have to be defined as well as, if possible, the expected behaviour of the system during simulation and all results that are relevant for the specific UC (input-related errors can be identified more easily this way).

It is expected that most simulations that will be done in the ELECTRA project can be performed in one single power system simulation software tool without the need of interconnection of multiple simulation tools (co-simulation) or coupling with hardware simulation (controller hardware in the loop / C-HIL or power hardware in the loop / P-HIL). Nevertheless, to increase accuracy of models of specific components, or to investigate the behaviour of specific hardware components in detail, co-simulation as well as C-HIL and/or P-HIL simulations will be performed in the lab, if necessary or useful. This integration and validation work is foreseen in WP7.

The final decisions, which parts of the investigated problems / test cases will be tested in the laboratory and implemented in real hardware, will be taken as soon as the complete list of test cases is available. The complexity of the investigated problems, the availability of appropriate testing hardware as well as the available options to create realistic test conditions will be incorporated into this decision process.

2.2.2.1 Generic programmable hardware platform

For demonstration and transfer to WP7 of working observable algorithms these should be either implemented into a programmable unit that can be used in WP7 or the algorithm has to be transferred to a unit already present in the lab. The units, in turn, should be generic enough, to cope with a wide range of possible implementations.

Typical test cases will require power hardware capable of generating arbitrary voltage and current curves, as well as voltage sources that are capable of emulating specific line impedances. Another example will be PV inverters emulating the missing inertia or being capable of other specific frequency control strategies. Furthermore, also hardware tests in laboratories that are capable of modelling LV grids with controllable secondary substation transformers can be possible.

Since the test cases defined may exceed the constraints and parameters of the available testing hardware, a list of hardware platforms with their parameters and constraints that are available within the project consortium will be created. This list will be matched with the test case list to see which laboratory tests are possible. Although the limitations of the laboratory framework should not influence the creation of the test cases, a modification of the test cases to fulfill the hardware constraints can be discussed.

2.3 Methodology - Balance Control

2.3.1 Used Methodology

According to the definition given in deliverable D5.1 [3] a control triple consists of a set of three key-elements:

- Control aim
- Observable
- System input signal

Therefore, the identification of control triples for balance control requires a clear identification of basic control schemes that are needed to realise the control processes. For the refinement of the selected control triples and their harmonisation with the proposed control taxonomy some iterations between defining them and control schemes will be used. To this end, the first step in this Sub-Task is the overview of the analytical Balance Control Use Cases as presented in D3.1 [2]. The basic information elements come from the UC templates included in that deliverable, and are the UC objectives and the step-by-step analysis of the individual processes. These data, in combination with the definitions and inventory of control triples presented in D5.1 [3], will be used in order for the consortium to identify and deduce the most appropriate control triples for the future Balance Control schemes.

The procedure is envisaged to have the following steps:

- Use of input data from Use Case analysis of D3.1
- Identification of control aims for each UC
- Identification and final agreement on the basic control loops that should govern the Balance Control UCs, with the aim of clearly identifying the input signals and the observables required for their effective operation
- Harmonisation of the finally identified control triples with the outcome of T5.1 and possible extension of the existing inventory of Control Triples.

In this context in the first part of this section we focus on the overview of the four Balance Control UCs by emphasising the control aims which are the key to devising the essential control loops involved in these UCs.

2.3.1.1 Balance Control UCs overview and basic control aims

According to the descriptions given in D3.1 [2] each type of Balance Control is concerned with one specific aim. Namely, the Inertia Response Power Control (IRPC) is intended for the very fast compensation of power imbalance in order to contain the Rate of Change of Frequency (ROCOF) during fast transients in frequency (both for small fluctuations in normal operation and large deviations due to contingencies). The Frequency Containment Control (FCC) is concerned with the compensation of the power imbalance and containment of the absolute frequency deviation (new steady-state frequency value). The Balance Restoration Control (BRC) aims for the restoration of frequency to its nominal value based on the absolute deviation together with the restoration of Tie Line power flows after deviation from their scheduled values as a result of imbalance. Finally, the Balance Steering Control (BSC) is concerned with the regulation of power flows and, consequently balance within the Cell of interest.

Figure 11 shows the possible activation intervals of each control scheme over time. It should be pointed out that for the completeness and the most efficient operation of the Balance Control UCs and particularly for the cases of IRPC and FCC, in which the response of reserves should be fast and always available, both of these UCs ought to ensure a specific amount of two quantities, namely:

- Total Cell Inertia (H_C)
- Network Power Frequency Characteristic for a Cell (λ_i)

The total Cell inertia determines the contribution of each Cell to counteract a sudden frequency change. In a nutshell the higher the total inertia is, the more immune the system will be to sudden balance changes, thanks to availability of sufficient amount of reserves which can provide the instant power for compensation of emerging frequency transients and dynamics. In addition, concerning FCC each Cell can proportionally contribute to the Web-of-Cells Network Power Frequency Characteristic (NPFC or λ_u). The contribution of each Cell defines a NPFC for the Cell (λ_i), which determines the absolute deviation of the Tie Line power for a frequency change [11]. Evidently, the value of λ_i influences the amount of reserves that the FCC will provide and also the initial conditions for BRC. It is worth mentioning that a specific amount for both Inertia and NPFC can be determined by mechanisms which schedule the availability of these reserves (i.e. day-ahead or intra-day market processes) but the observation and control of these quantities allows each Cell Operator to regulate and ensure specific levels for these quantities in real time. In other words Cell Operators use control loops to compensate uncertainties in the values of H and NPFC that cannot be accurately determined by a market (or any other scheduling) process. The accurate control of these parameters by real-time loops is something crucial for the cell's stability because the time scales of these actions are too small for an operator to proceed to other corrective actions. Hence an accurate regulation of these parameters is a prerequisite. Therefore, taking into account the control aims of each Balance Control UC the following table (Table 2) which summarises the type and control objectives is obtained.

Table 3: Overview of Balance Control Use Cases and corresponding Control Aims

Type of Balance Control	Control Aim
Inertia Response Power Control (IRPC)	Objective 1: Reacts to frequency changes over time (frequency transient plus dynamic response) Objective 2: Observes and regulates in real time the available amount of inertia within a Cell
Frequency Containment Control (FCC)	Objective 1: Reacts to deviations of the frequency value so as to contain any change and stabilise frequency to a steady-state value Objective 2: Observes and regulates in real time the NPFC or λ_i within a Cell
Balance Restoration Control (BRC)	Reacts to absolute frequency deviations in conjunction with the tie line power flow deviations from the scheduled interchanges so as to restore both quantities to their initial values

Type of Balance Control	Control Aim
Balance Steering Control (BSC)	Regulates power balance within a Cell (proactively or reactively) in order to replace BRC reserves or mitigate potential imbalances in a cost effective manner

According to the conceptual implementation of the four schemes above and considering both the primary and secondary control aims each scheme has a specific activation profile which is shown in Figure 11:

- IRPC can automatically be invoked at any moment regardless of the system state (either normal operation or contingency) as long as frequency dynamic changes emerge due to imbalances or transients due to faults occur [12]
- BSC can also be invoked at any stage except right after an incident that triggers BSC activation only after FCC and BRC commencing.
- FCC is automatically commenced by an incident that leads to any frequency deviation beyond a threshold so as to maintain frequency stability [13].
- The combination of frequency and Tie Line power flow deviation leads to commencing of BRC after an incident. Invoking of BRC always follows that of FCC and it requires the frequency quasi-stabilisation.
- At particular time intervals the action of more than one controller may take place; however, only one is always predominant at a time.
- The operation of IRPC that aims at observing and regulating H_C and that of FCC responsible for observing and regulating λ_i are continuous apart from the intervals of imbalance contingencies where they should be inactive for security reasons.

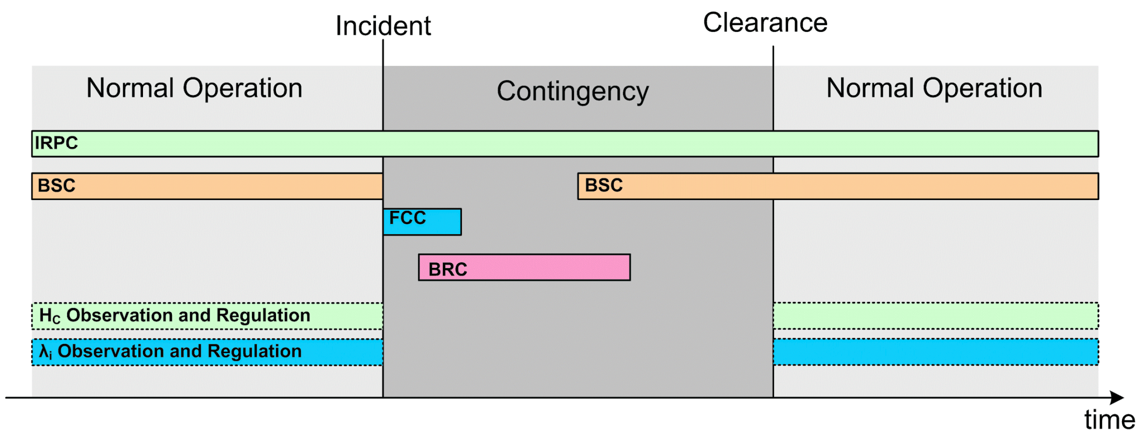

Figure 11: Activation timeframe for all four Balance Control schemes

2.3.1.2 *Analysis of control aims and proposed basic control schemes*

The analysis of the control aims and resulting operation of a system consisting of a Web-of-Cells is based on the following assumptions:

- The changes happening in the system refer mainly to dynamic stability (also known as small-signal stability) phenomena which assume that the imbalance disturbances are relatively small (e.g. loss of generator) compared to those disturbances caused for instance by faults [12] although the latter can also lead to loss of units after their clearance.

Therefore, all these phenomena result in frequency departures with the risk of instability [13] in which the analysis below refers to.

- The only control scheme that contributes to frequency transients compensation (i.e. due to faults) in terms of containment of rate of change of frequency is that of IRPC. Inertia as a physical property of synchronous generators intrinsically reacts instantaneously to transients of frequency (or more precisely to rotor angle deviations) caused by severe imbalances due to faults or less severe imbalances due to load/generation changes. Therefore, the future IRPC scheme, besides providing system support to dynamic stability, should also be able to provide system support in case of faults, helping the system to maintain stability until the fault is cleared.
- The system consists of interconnected Cells, forming a Web-of-Cells, via tie-lines the capacity of which can generally - but not exclusively - be regarded as small compared to the Cell rated power. As the main scenario of the analysis it is considered that the tie lines are not controlled whatsoever during incidents. This is a means of supporting unbalanced Cells by power contribution of neighbouring Cells [2]. However, for a more holistic approach in ELECTRA the scenario of tie-lines equipped with frequency decoupling systems or other type of control should also be considered in terms of the resulting observables and control triples.
- The disturbances in balancing may result in oscillations. As a matter of fact one or more Cells can be regarded as oscillating synchronously (all generators undergo the same frequency variations), simplifying so the analysis and the system representation. The specific assumption is made on the grounds that control areas in power systems analysis in literature are treated as a single entity in terms of frequency dynamics. This approach is also regarded for cells and, thus, a cell is governed by an equation of the following form:

$$\Delta P_{Gi} - \Delta P_{Di} = \frac{2Hi}{f_o} \cdot \frac{d(\Delta f_i)}{dt} + D_i \Delta f_i + \Delta P_{Tie,i} \quad (2.1)$$

where ΔP_{Gi} is the variation in generated power, ΔP_{Di} is the variation in consumed power, H_i is the cell's inertia constant, f_o is the nominal frequency, D_i is the load self-regulation coefficient, Δf_i is the frequency variation and $\Delta P_{Tie,i}$ the variation in the tie line power flows.

The control aim analysis is supported by a simplified example of 4 interconnected Cells under different operating and control stages. This example is shown in Figure 12 and it also helps explain the operation of BRC after an incident. Taking into account the above assumptions and the control aims presented in the previous section, the expected result of the first three Balance Control schemes, namely IRPC, FCC and BRC, on frequency is summarised in Figure 13. In particular, Figure 13 (top diagram) illustrates the frequency response of the Cell after an incident that results in frequency decline. Also, Figure 13 illustrates the corresponding total tie-line power flow deviation in the disturbed Cell and the effect of BRC on it after its activation. Obviously, if the tie-lines of the Cell are equipped with appropriate control system such as frequency transformer, HVDC link or other type of control, the deviation of the tie-line power will be zero (or less than a maximum depending on the control implemented). Therefore the scenario becomes simpler and only the unbalanced Cell undergoes frequency deviation, while the adjoining Cells remain unaffected. In other words, the unbalanced Cell is isolated in terms of reserves. This strategy has some trade-offs with regard to reserves within the Cell but ensures a more robust Balance Control for the Web-of-Cells. In any case it is a potential scenario and therefore it is taken into account not as a separate analysis but as special case of the main scenario. By contrast, BSC's aim is to steer power flows and, therefore, its control aim is separately depicted in Figure 14.

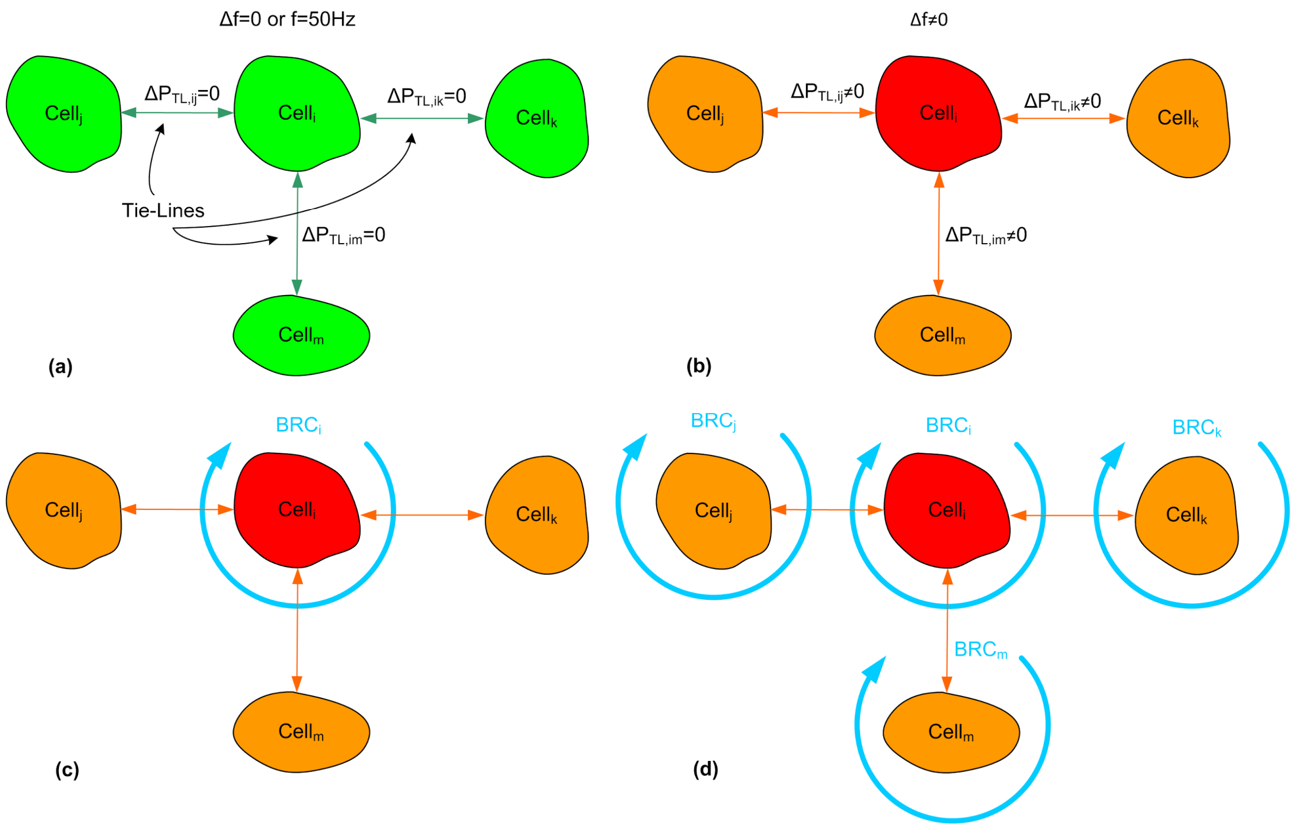

Figure 12: Example of four interconnected Cells through various operation and Balance Control stages

Initially, the system operates under a balanced state (Figure 12a) where both the frequency and tie-line power flow errors are zero. At t=0 a balance deviation, such as a load step change causes a power deficit in the central Cell. The disturbance will instantly initiate a frequency change which triggers the reaction of IRPC, and FCC in all four Cells. Therefore, at the first moments (t<5 s) after the incident an activation of IRPC is expected in order to minimise the Rate-of-Change-of-Frequency (ROCOF). Although the dynamic response may vary for each Cell, the overall behaviour is similar and therefore an activation of IRPC and FCC reserves in all Cells is inevitable, unless the Cells are decoupled in terms of frequency as mentioned previously.

However, during the initial phase and due to the small difference between the actual and the nominal frequency, the contribution of FCC is rather negligible for all Cells until some time elapses. As the frequency deviation evolves and the ROCOF reduces, the contribution of FCC becomes predominant (same for all Cells) while IRPC wanes. As a result, the combined action of both controllers yields the minimum (or nadir) of frequency after a time t_{min} while, as can be seen in the bottom diagram of Figure 13, the total tie-line power flow deviation is positive $\Delta P_{TL,i}>0$. The corresponding deviation for the adjoining Cells will be negative. The resulted situation is a stable situation (Figure 12b) in which the frequency is common for all Cells and the central Cell imports a part of the total power required for balancing from the adjoining Cells. Inevitably, the maximum frequency deviation value or $\Delta f_{i\text{-}dyn,max}$ in combination with the instant t_{min} that the nadir happens, constitute a means or metric for the performance assessment of both IRPC and FCC controllers.

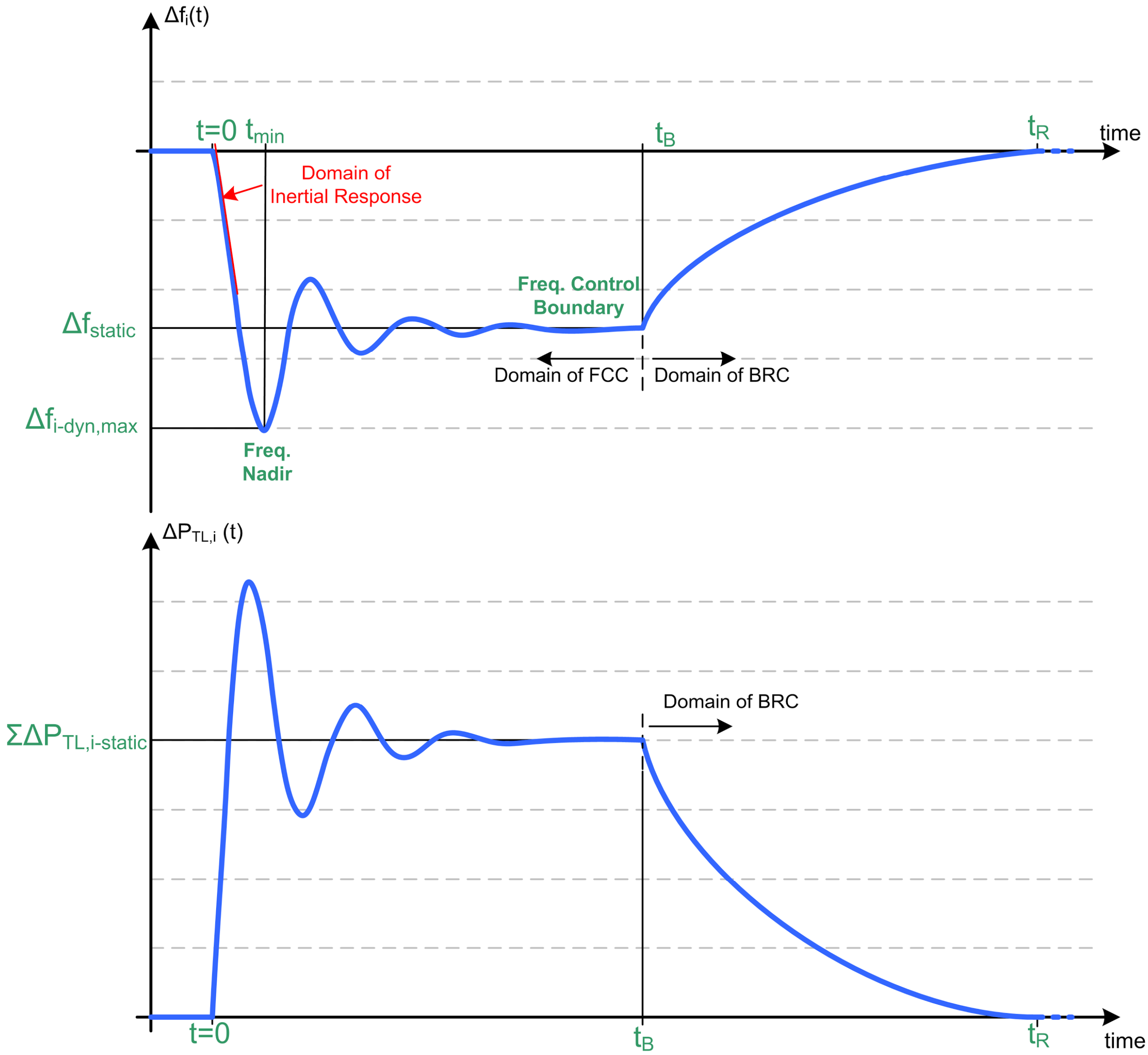

Figure 13: Evolution of frequency and tie-line power flow: control aim of combined Inertial, FCC and BRC over time after an incident within the unbalanced Cell

After the first phase has elapsed and the action of FCC leads to frequency stabilisation to a nearly steady-state value which is below the nominal one, the BRC takes over to restore both frequency and the tie-line power flows. This is assumed to happen after a time t_B (between 30 and 60 s), when BRC takes over so as to restore frequency and tie-line power flows to the initial values. This can be done either by activating the control scheme within the Cell that causes the imbalance [12] (unilaterally, Figure 12c) or by the coordinated activation of the adjoining Cells' BRC controllers too (Figure 12d). In any case, the activation of multiple BRC controllers should be such that the stability is not jeopardised [11]. Also, the key quantity that BRC should observe and try to minimise is the Balance Restoration Control Error, given by the formula:

$$BRCE_i = \sum \Delta P_{TL,i} + K\Delta f \qquad (2.2)$$

This error is the equivalent to the Area Control Error and is independent of the control strategy that each BRC implements. It depends, however on the type (control) of tie-lines. If the tie-line power is controlled by one of the abovementioned methods, then the first terms of BRCE for the tie-lines becomes zero, simplifying so the control objective. It is assumed that the BRC is completely inactive before the time t_B and the control constants are such that it is much slower than IRPC and FCC, avoiding so interference and potential instability issues.

The BRC process lasts until time t_R which is of the time scale of 300 seconds when the final Δf and $\Sigma\Delta P_{TL}$ values have to be zero before the BSC takes over. At this time, the BRC reserves of the central cell are still active, while FCC and BRC (if they are used in a coordinated control) of all adjoining cells will have become inactive due to their complete substitution. In this case the values of Δf_{static}, t_B and t_R can be used as metrics for the performance assessment of both FCC and BRC.

By contrast, the control aim of BSC partly differentiates from those of the other three control schemes. In particular, the scope of BSC is the fulfilment of specific active power set-points either in reactive or proactive mode, always ensuring the cost-effective operation of resources. In Figure 14 (top diagram) the reactive mode of BSC is illustrated. The process is the following: after time t_R has elapsed, the BS resources are gradually deployed so as to supplant the already deployed BR reserves. Obviously, this may entail a rescheduling of the tie-line power flows as well, but in contrast with the uncontrollable imbalance incidents, this is now done intentionally and without affecting frequency, in order to utilise the optimal resources and make BRC available for potential future incidents. Thus, the final goal, as shown in the top diagram of Figure 14, is the achievement of a specific aggregated active power level within the Cell for a specific time duration. During the activation of BS resources and until time t_S when the set-point is met, there is a simultaneous gradual withdrawal of BR reserves. The latter have to be synchronised and completely withdrawn at t_S as well so that there would be no control conflict which can lead to imbalance with subsequent frequency deviation. At present, the use of the corresponding Tertiary Frequency Reserves to substitute the already activated Secondary Frequency Reserves is mainly obtained manually. In the ELECTRA view of the future power system both controls will be automatic and, therefore, a good coordination of the control parameters is necessary so as to avoid potential conflicts or runaway effects that could pose a threat to the system stability.

The case of proactive use is separately shown in the bottom diagram of Figure 14. For the sake of simplicity and clarity a simple example has been considered. This diagram illustrates the power profiles of a Cell, including the aggregated generation P_G, demand P_D and tie-lines interchanges P_{TL}. Under normal operation all three profiles follow the scheduled ones leading to a zero or almost zero imbalance. This situation is shown with solid lines in the diagram.

However, it is possible that due to unpredictable intermittent behaviour of sources and loads deviations from the scheduled profiles happen. These are shown in dashed lines and result in imbalance values different from zero. The aim of BSC in this case is to intervene on time so as to supply with an opposite sign power and, hence, compensate imbalance. Therefore, the dashed parts of the imbalance profile line constitute the set-point profiles for the BS resources in proactive mode. It should be stressed that these profiles should be obtained by a short-term forecasting tool used by the Cell operator, rather than real-time measurements only. This means that the activation of BS resources should precede the imbalance deviation, in order to make sure that the activation happens on time and not with a time delay that could lead to frequency instability. Also, the effective deployment should be done by means of observing frequency deviations in order for the BSC to make sure that it does not deploy excessive amounts of resources that could have the opposite effect to the system balance. The accuracy and effectiveness of the BS resources deployment is achieved as long as frequency remains within pre-specified limits. Provided that, activation of other controllers such as FCC and BRC are avoided but even if that is not the case, the decrease of imbalance provided by BSC will mitigate the imbalance effects making the use of FCC more effective.

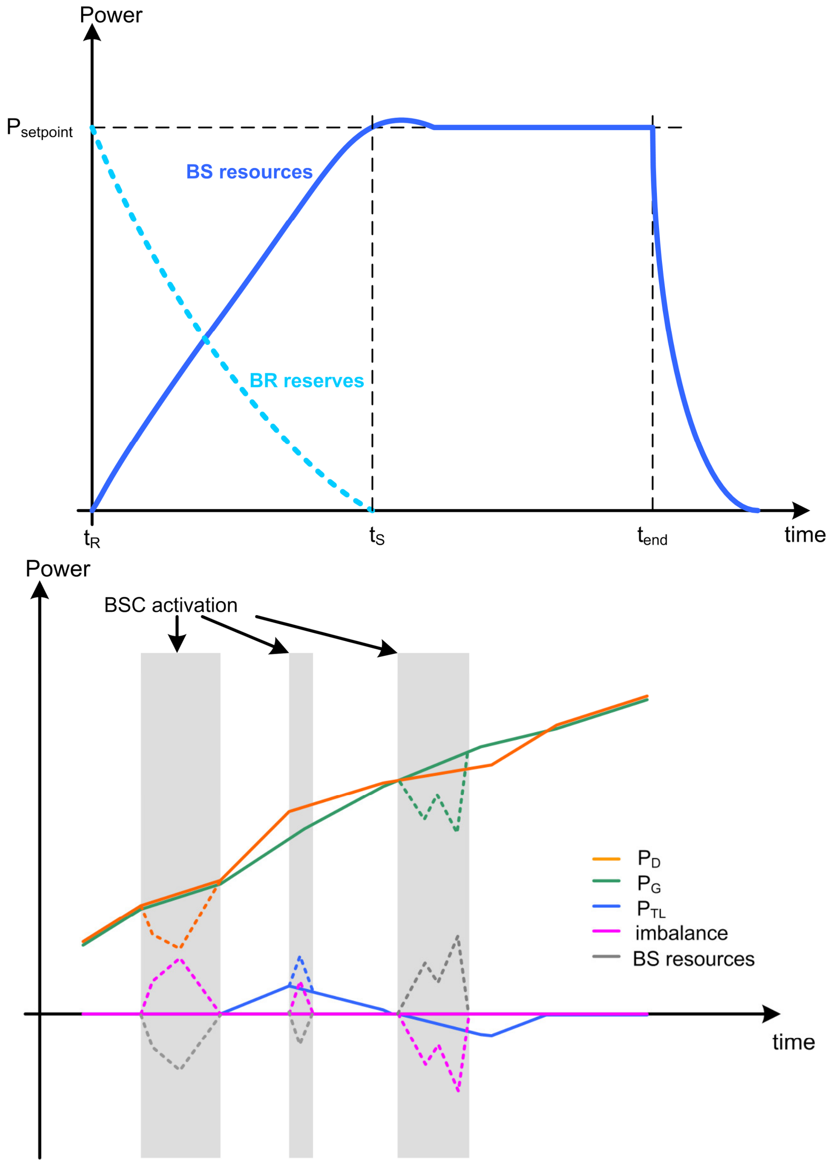

Figure 14: Evolution of real power and control aim of BSC in both reactive (top diagram) and proactive (bottom diagram) mode

Finally, one of the main objectives of Inertia Steering Control is to observe and regulate in real time the total inertia located within the concerned Cell. This distinction in responsibility level can be made due to the assumption that the dynamic frequency response may vary from Cell to Cell. Thus, as long as one frequency profile is assumed for one Cell, then the Cell operator by means of the control centre has the responsibility of observing and regulating the inertia which, in combination with FCC determines the most crucial initial frequency deviation (Initial ROCOF and minimum/maximum frequency). The importance of the first moments of a frequency deviation lie in the fact that protection systems may be affected by the initial response of frequency, leading to cascade effects and possible black-outs. In addition to the regulation of inertia, one of the most important Tasks for the stable system operation is the regulation of the Network Power Frequency Characteristic (NPFC or λ) and, particularly the contribution of each Cell to the total system λ_u which defines the contribution of Cells to the FCC. This latter process is also largely linked to control centre actions.

2.3.2 Methodology - Sub-Task 5.2.1.Identify needed Control Triples from Use Cases

The previous analysis, which focuses on the high-level description of control objectives, is used as the basis for identifying the needed control triples for the Balance Control UCs considered in ELECTRA. This identification is strictly related to deducing basic control block diagrams based on the control objectives description of section 2.2.1. These diagrams should be as general as possible in terms of the control blocks used, because the elaboration of them is part of other Tasks. These diagrams ought to explicitly depict the control aims, the observables towards those aims and finally the input signals that are required for the system to appropriately respond to the controller actions. These diagrams are to be analytically presented and explained per UC.

2.3.2.1 Definition of Observables needed

By means of the basic control diagrams derived from the control aims analysis it is possible to identify which physical or other quantities are necessary as an input signal for each controller. These observables will be obtained by actual measurements of voltages/currents at specific points in the Web-of-Cells using selected calculation blocks which are elaborated in the sections below. Each observable for each control loop constitutes the real signal which is compared with the reference value. For instance, with regard to FCC, the instantaneous frequency should be observed and compared to a reference value so as to calculate an appropriate active power set-point for a unit participating in FCC. The needed observables will be analytically presented for each UC and control scheme. The analysis is accompanied by theoretical models for defining these quantities.

2.3.2.2 Known Control Triples

After having identified the control aims, the basic control schemes and the needed observables, the last step in the process involves the identification of the input signal, needed to complete the identification of the control triples. As the system input signal we consider the physical quantity which is supplied to the system in order for the system to behave as determined by the control loop. Due to the generic nature of Balance Control the system that we consider in the analysis is the behaviour of Cells in the Web-of-Cells. This is assumed because balance control has system-wide effects. Also, the input signal in the vast majority of Balance Control loops is instantaneous active power. Having known the input signal in conjunction with the observable(s) and the control aim, a list of control triples is derived. Part of this comprises the already known control triples, also identified in the frame of T5.1 [3].

2.3.2.3 New Control Triples

The identification of new control triples for balance control requires a similar methodological approach as in the case of the known ones, with the exception that the exact details are defined by the previous methodology analysis in conjunction with the classification of control schemes in topology and time scale levels. In other words, the analysis takes into consideration the control objectives based on the high-level control aims of the four Balance Control UCs, and with the adoption of the topology and time scale levels specified in T6.2 [9] the new control triples are selected so as to meet the needs of the control implementations. The following assumptions are made:

- The resulting New Control Triples must be unambiguous with regard to selecting, implementing and testing each of them. Also, this is critical for the analysis of the WP6.2 control algorithms since there is a close interrelation between the two Tasks.
- In addition, they must be generic, which means that they should only refer to general implementation at each Control Topology Level and Control Time Scale.

- Each Balance UC which can be described by a set of cascaded controllers/systems will have to be sufficiently covered by relevant control triples at each individual level.
- Finally, wherever Known Control Triples fully or partly cover specific control requirements, these should be retained or used as a base to develop the corresponding new ones.

2.3.3 Methodology - Sub-Task 5.2.2.Determination methods for specific observables

2.3.3.1 Algorithms

In the Spreadsheet "Use Cases-Control Triples" Tab:"WP5 Observable Algorithms" [18] relevant observables for the ELECTRA Use Cases are listed.

New observables like e.g. the local power balance of a grid part or the inertia response power to be delivered to counteract frequency changes call for faster and more accurate information about the actual value and the frequency of voltages, currents and power. There is a need to know these values on a time scale of one or a few cycles and sometimes even within one cycle. An assessment will be made of the Clarke and/or Park transformations as an adequate technique to meet these requirements. The requirements for the acquisition of these values will be investigated as well as the requirements for the post-processing in order to derive meaningful observable values.

The situation at normal operation of the grid is investigated as well as circumstances where the phase quantities are heavily distorted or deviating strongly from rated values.

2.3.3.2 Determination methods for specific observables

Active and reactive power are conventionally defined in the time-domain implying sinusoidal voltages and currents. The definition of instantaneous active power is just the multiplication of voltage and current. Reactive power is defined for a whole sine voltage period as the maximum value of the corresponding actual power, which has an average of zero. Inertial response power is proportional to the time derivative of grid frequency, which counteracts changes in grid frequency.

Akagi and other authors [17] have developed the concept of instantaneous (reactive) power. This concept starts with decomposition of instantaneous power and current into real and reactive components, according to Clarke or similar transformations. The significance and usefulness of this concept will be investigated for defining instantaneous values of other quantities like frequency and inertial response power.

2.3.3.3 Measurements

The observability functions are fundamental elements in monitoring the secure operation of a power system, since they enable to estimate the system state. Adequate and reliable measurement devices are needed that monitor the variables describing the network operating point, for example: currents, voltage, frequency, active and reactive power, etc. These variables are *permanently* measured and compared with setpoints or thresholds beyond which the situation is defined as abnormal and can lead to instability. When a deviation from normal operation, or even a contingency, occurs, the controller device issues a signal operating a flexible source.

Permanent monitoring of the network's electrical values by reliable and proper measurement devices supplying controllers is a key element of the control loop of the Balance and Voltage Control schemes allowing a rapid reaction and the stabilization of the network.

So, the definition of the measurements requires a strict technical specification of the measurement devices. The document in the "*Annex: The measurements chain in function of control objectives*" provides some basics when defining the measurements chain: current and voltage transformers, analogical to digital conversion and calculation algorithms.

The next figure presents the general block diagram of the whole measurement chain. The first elements of this chain are the measurement transformers. The values of voltage or current in an electrical network are too high to permit convenient direct connection of measuring instruments or relays. Measurement transformers are then required to produce a down-scaled replica of the input quantity (to the accuracy expected for the particular measurement, of course).

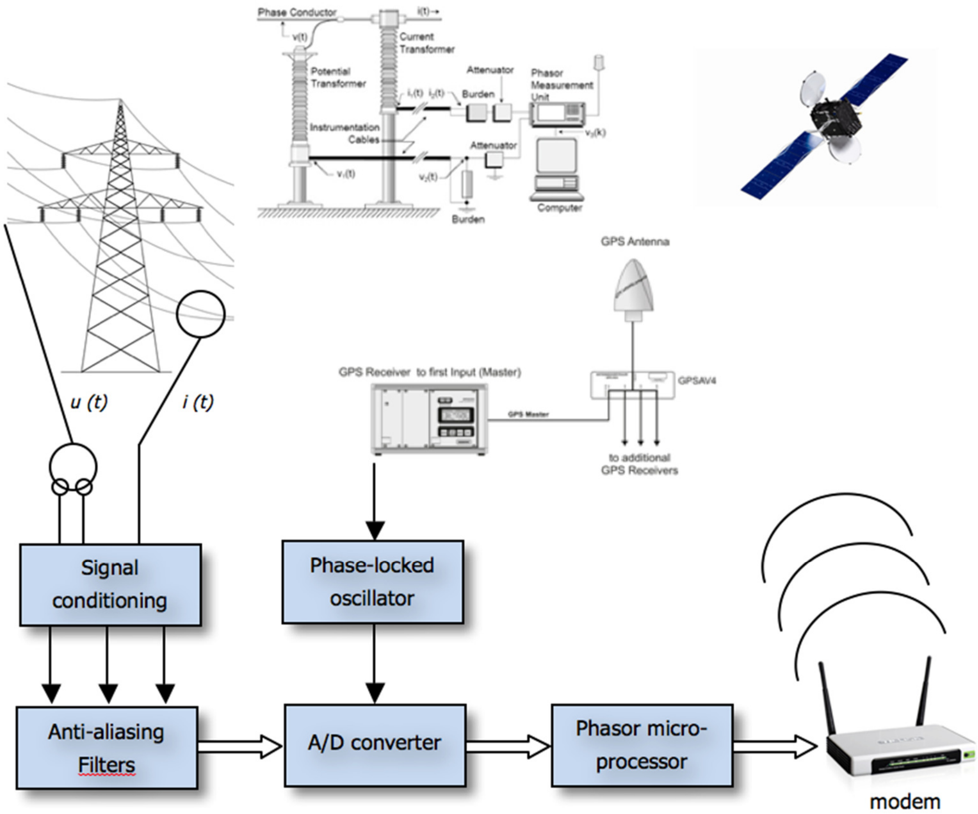

Figure 15: General block diagram of the measurement chain.

The performance of measurement transformers during and following large instantaneous changes in the input current or voltage is important, in that this input may depart from the sinusoidal waveform. The deviation may consist of a step change in magnitude, or a transient component that persists for an appreciable period, or both. The measurement transformers and the whole measurement chain are required to operate accurately during the period of transient disturbance characterizing the network contingency. An error in the measurements may abnormally delay the operation of the controllers or cause unnecessary operations.

The measurements of currents and voltages are then conditioned before being converted to digital values by Phasor Measurement Units (PMU). Signal conditioning may be necessary if the signal from the measurement transformer is not suitable for the Data Acquisition hardware being used. For example, the secondary current given by the CT will be converted into a voltage signal that will be easily handled by the A/D converter. The signal may also need to be filtered to limit the bandwidth (anti-aliasing filter and data sampling frequency satisfying the Nyquist criterion) and avoid errors in the digitization process.

The data acquisition process and the synchronisation of the measurements are then realised by PMUs. The PMUs are power system devices that provide synchronized measurements of real-time phasors for the voltages and the currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) Satellite. Time synchronization allows synchronized real-time measurements of multiple remote measurement points on the grid.

Data acquisition is the process of sampling the input signals – voltage and current – and converting the resulting samples into digital numeric values that will be treated by a computer to determine the observables. This process is illustrated in the figure below.

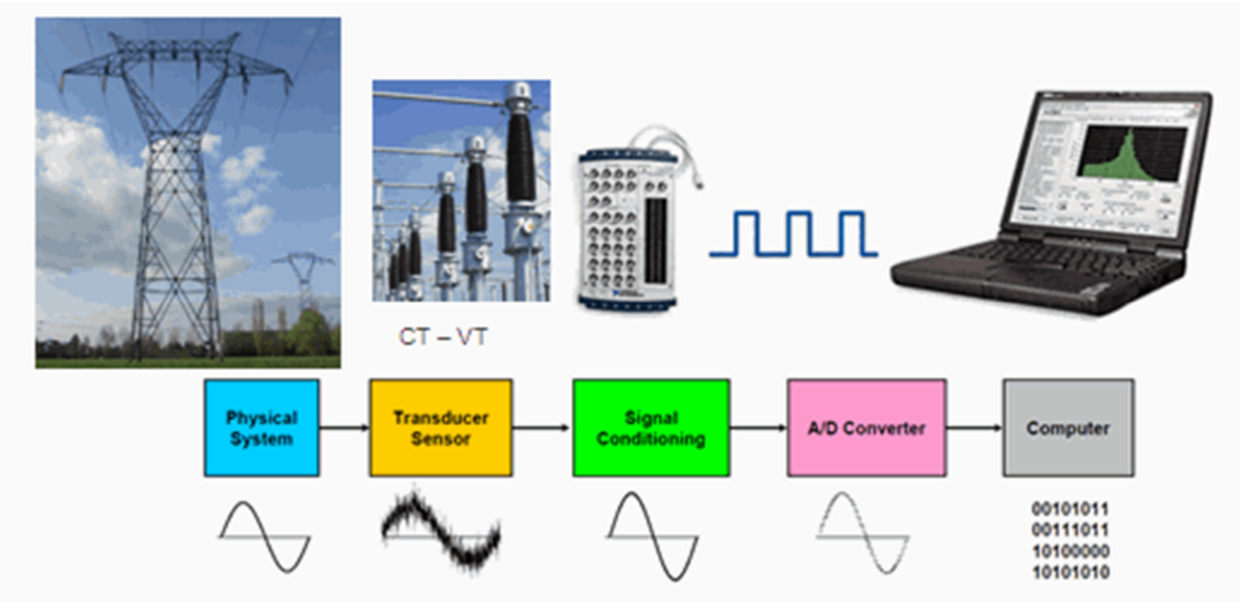

Figure 16: Data acquisition process.

A phasor is a complex number that represents both the magnitude and phase angle of the sine waves like the currents and the voltages. The most common technique for determining the phasor representation of an input signal is to use data samples taken from the waveform, and apply the Discrete Fourier Transform (DFT) to compute the phasor. Sample frequency could vary, regarding the level of supervision needed voltage or balance control).

Phasor measurements that occur at the same time are called "synchrophasors". Phasor measurements are sampled from widely dispersed locations in the power system network and synchronized from the common time source of a Global Positioning System (GPS) radio clock.

PMUs measure voltages and currents at critical points on the power grid and they output accurately time-stamped voltage and current phasors. Because these phasors are truly synchronized, synchronized comparison of two quantities is possible in real time. These comparisons can be used to assess system conditions such as frequency and voltage changes. The phasor data is collected either on-site or at centralized locations using Phasor Data Concentrator (PDC) technologies and Supervisory Control and Data Acquisition (SCADA) systems. The data is then transmitted to a monitoring system allowing the computation of the observables (for different control triples and the control of the power flows on the network).

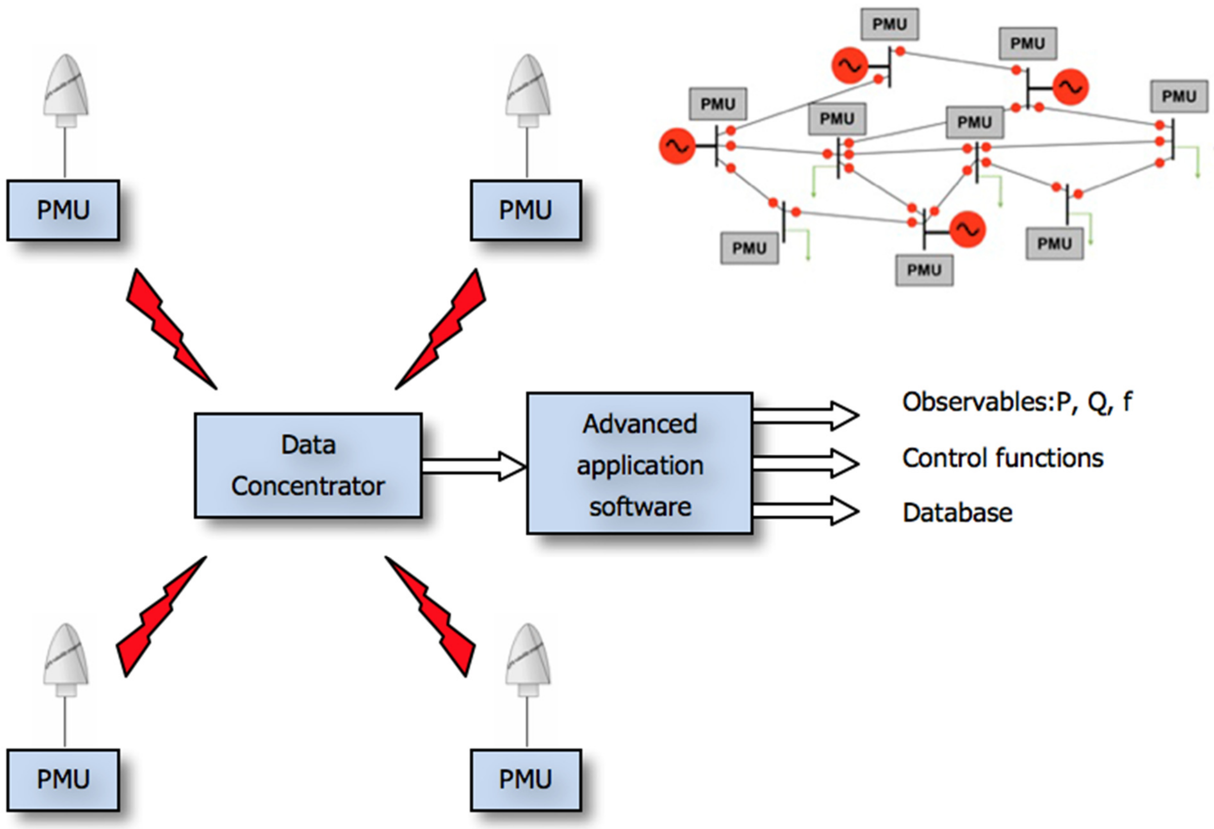

Figure 17: Integration of PMUs in the power systems.

The requirements for IT infrastructure to guarantee 'real time' data exchange are out of scope in this document but it is worth to mention the application of IEC 61850 protocol that is of great interest in electrical power systems for data communication systems between substations. This IEC 61850 protocol offers new possibilities for real-time communication performance between Intelligent Electronic Devices (IEDs) within substation and between substations and the observation and monitoring center because of the Generic Object Oriented Substation Event (GOOSE) messages.

Reliable measurements should also provide quantification of measurement error. This error could vary, as a function of the level of supervision and the precision required for the observables algorithms of each control triple.

2.3.3.4 Numerical reliability tests

As explained in the previous paragraphs for Balance Control, some of the new observables need to be defined as instantaneous values if possible. Therefore the algorithms determining these could suffer from background noise that is not cancelled by some averaging procedure. As e.g. inertial response power is proportional to the time derivative of instantaneous frequency, also numerical noise may be a serious problem.

The verification of the numerical reliability and the robustness of the algorithms will be done in the following two steps:

- Identification of the influencing factors (background noise, numerical noise, bad input data, measurement errors, etc.)

- Sensitivity analysis of the identified factors: how the variation of each one is affecting the output of the algorithms. (The observable calculation and the entire basic control loop convergence.)

Results of the tests can provide the first insight to improve the algorithms on one hand, and/or apply appropriate measures during the measurement acquisition phase (for example, filtering) on the other hand. Normally a more robust algorithm costs more computationally, which maybe is not a problem for a basic control loop but can become an issue when the number of network nodes (and controllers) increases.

2.3.4 Methodology - Sub-Task 5.2.3.Basic control loop simulation, based on chosen Control Triples

2.3.4.1 . Basic control loop simulation

In the frame of this Task a set of simulations is planned. The simulation tests aim at providing a means of assessment of the selected Control Triples and particularly how the observables' algorithms perform within a closed-loop system. For the generic control loops describing each Balance Control UC, specific simulation models will be developed, to provide a testing environment for the evaluation of consistency and effectiveness of each control triple. Obviously, particular care will be devoted to the algorithms/methods selected to measure/calculate the specific observables and how these observables' blocks interact with the relevant control algorithms. In this context the specific Task will have to take into consideration the outcomes of three Sub-Tasks:

- The identification of observable algorithms (in conjunction with the relevant control triples),
- The SRPS (Single Reference Power System) analysis, and
- The controllers' analysis provided by WP6.

Concerning SRPS analysis, a (set of) solution(s) with regard to the power system models that can be used will be considered. In fact, the analysis should assume simplified representations of power systems sufficient to provide the information/behaviour necessary to test the observables algorithms. This approach is expected to:

- Minimise efforts of setting up and modifying the system model
- Minimise simulation tests time
- Increase test repeatability

In addition, from the outcome of T6.2 an exhaustive list of control algorithms will be derived. This list can be used by the T5.2 working group in order to opt for the most appropriate control blocks to be tested together with the observables' blocks. Since the focus will not be the elaborate analysis of controllers themselves (this is part of WP6), the controllers selection should be made based on the above mentioned facilitation criteria to this Task's tests.

It is worth noting that as far as this is necessary initial tests with simplified input signals can be implemented as first-round of tests for observables' algorithms (e.g. variable frequency signal generator to test PLLs).

2.3.4.2 Reliability test

The overall methodology for the reliability tests will be similar to that outlined in section 2.3.3.4 for the numerical reliability testing. However, new influencing factors to consider can appear when the algorithms are implemented in a real hardware prototype at laboratory level. In addition, tests shall be performed in normal and undesired conditions (reproducing some disturbances, for example). A clear test plan shall be prepared for guiding the tests and collecting the results.

2.3.5 Methodology - Sub-Task 5.2.4.Hardware test (lab table)

2.3.5.1 Lab table programmable unit test to be transferred to WP7

As described in Chapter 2.2.2., simulations will be primarily performed with power system simulation software tools. The decision about which simulations will be implemented in hardware and elaborated in lab tests will be taken when all test cases are defined and the capabilities of the evaluated hardware test platforms are evaluated [8].

The interface between the software simulation and the hardware simulation depends on the type of simulation and the type of hardware. Therefore the unit test input and output signals and parameters have to be developed from the test cases for each individual simulation. A comprehensive documentation of the test cases provides all information needed for software as well as for hardware simulations.

The following points have to be elaborated to gain the test setup for the testing hardware from an existing test case:

- Define the lab wiring according to the grid model and the impedance parameters given by the models defined in the test case
  - Define the involved component(s) and measurement device(s)
  - If the grid model has to be reduced to be realizable in the lab, the simulated grid impedance has to be calculated.
- Realize the test setup
- Configure the devices
  - Configure the grid simulator(s) for all relevant parameters according to the time series given by the test case.
  - Configure the measurement device(s) according to the parameters defined in the test case.
  - Configure the testing hardware according to the parameters defined in the test case.

2.4 Methodology - Voltage Control

2.4.1 Used Methodology

The application of a general methodology to the Voltage Control UCs is parallel to the previously explained in section 2.2.1 of this deliverable for balance control. The identification of the control triples (control aim + observable + input signal) required to fulfill the objectives of the future voltage control schemes roots on the identification of the basic control loops for every Voltage Control UC. The UCs details were shown in D3.1 [2], but here,a reminder will be done in the following section, in order to get the essential information for the identification of the control triples that will be implemented in future voltage control schemes.

The process to reach the expected results can be summarized as follows (see also Chapter 2.1.2. Working procedure for selecting observables and their algorithms):

- Identification of the control aims from the Voltage Control UCs.
- Identification of the different basic control loops for every UC, depending on the technology and the specific observables needed for the control of the distributed generation units.
- Harmonization with the results from T5.1 and extension, if necessary, of the existing inventory of control triples.

2.4.1.1 Voltage Control UCs overview and basic control aims

From D3.1 the necessary information about the Voltage Control UCs can be collected. The novel control scheme proposed for voltage regulation in 2030+ grids is intended to be accomplished in two steps: primary voltage control (PVC) and post-primary voltage control (PPVC). This means that the mechanisms for voltage control are simpler if compared with the ones required for Balance Control. On the one hand, the control aim for primary control is the stabilization of the voltage level at the nodes of the cells in case of a severe disturbance by adjusting the reactive (or active) power exchange at the point of interconnection with the device. On the other hand, the PPVC aim is the restoration of the voltage levels in the nodes of the Cells to their rated values (within a safe band) while optimizing the reactive power flows. A summary table of the voltage control UCs and their control aims is reported in Table 3. As a consequence a reduction of the losses of the network is achieved. This two-step voltage control scheme, by using the capabilities linked to the Web-of-Cells (mainly the high observability and monitoring of the Cells and the tie-lines for all voltage levels) will allow a safe, reliable and efficient voltage control mechanism. This voltage control hierarchy presents the advantage of being finished in only two steps as one of the main differences if compared with the current scheme.

Table 4: Overview of Voltage Control UCs and corresponding control aims

Type of Voltage Control	Control Aim
Primary Voltage Control (PVC)	Objective 1: Reacts in case of voltage deviations detected in any nods of a Cells as a consequence of a severe disturbance Objective 2: observes, monitors and regulates the voltage levels deviations in real-time in the grid nodes within the Cells
Post-Primary Voltage Control (PPVC)	Objective 1: Restores the voltage levels in the grid nodes to the set-point values within in a safe band Simultaneously, it optimize the reactive power flows in the system. Objective 2: regulates the voltages in the nodes in case of generation-demand imbalances

The PVC is an automatic control scheme that operates in case a deviation over the voltage set-points is detected in any node of the Cell. The activation of the reserves for the provision of this service has to be accomplished in the range of milliseconds. Each Automatic Voltage Regulator (AVR) type unit is responsible of its contribution to the PVC. The mechanism for the provision of PPVC reserves is more complex. Every Cell must have its own reserves but due to security or economic reasons, it can utilize reserves placed in its neighbouring Cells, by previous checking of the tie-lines transport capacities and the security of the reserves switching operation.

Considering the activation timeframes for the voltage control mechanisms, a timeline with the interactions of the voltage controls and the event that triggers their operation can be observed in Figure 18.

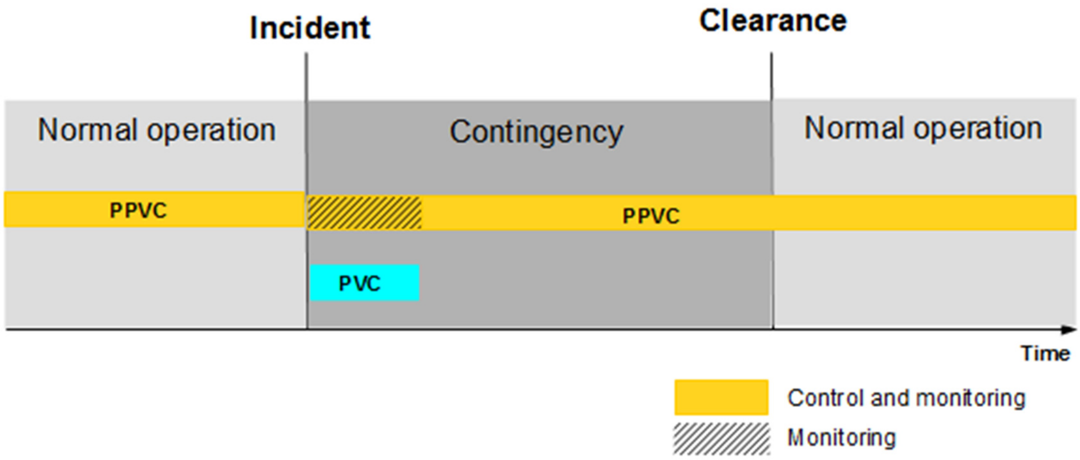

Figure 18: Activation timeframes for voltage control schemes

2.4.1.2 Analysis of control aims and proposed basic control schemes

The analysis of the control aims for the Voltage Control use cases is based, of course, on the application to the Web-of-Cells architecture, i.e. to a system formed by a group of interconnected Cells (the Web-of-Cells), linked by means of tie-lines (see details in D3.1 [2]) and such that the capacity for transporting active and reactive power by the tie-lines connected to a Cell is small if compared with the availability for active and reactive power provision within each Cell.

The operation mechanism is summarized as follows. At $t = 0$, a voltage disturbance is produced in the system, for example a voltage dip. As a consequence, at the point of the grid where the incident has occurred, there will be a sudden voltage drop that will spread to the whole Cell and it could affect a larger area than the Cell itself. This will cause the alteration of the voltage levels in the nodes of the neighbouring Cells of the node with the primary disturbance too. The detection of the voltage deviation in any node of any Cell will automatically trigger the primary voltage control in the units with the possibility to provide this service. The expected results of the activation of the voltage control mechanisms in a Cell are shown in Figure 19. In one of the nodes a deviation of the voltage over the setpoint (Vst) is detected. The PVC activates the resources in order to bring back the voltage to the safe band delimited by the minimum ($Vmin$) and maximum ($Vmax$) in a recovery time (t_{rec}).

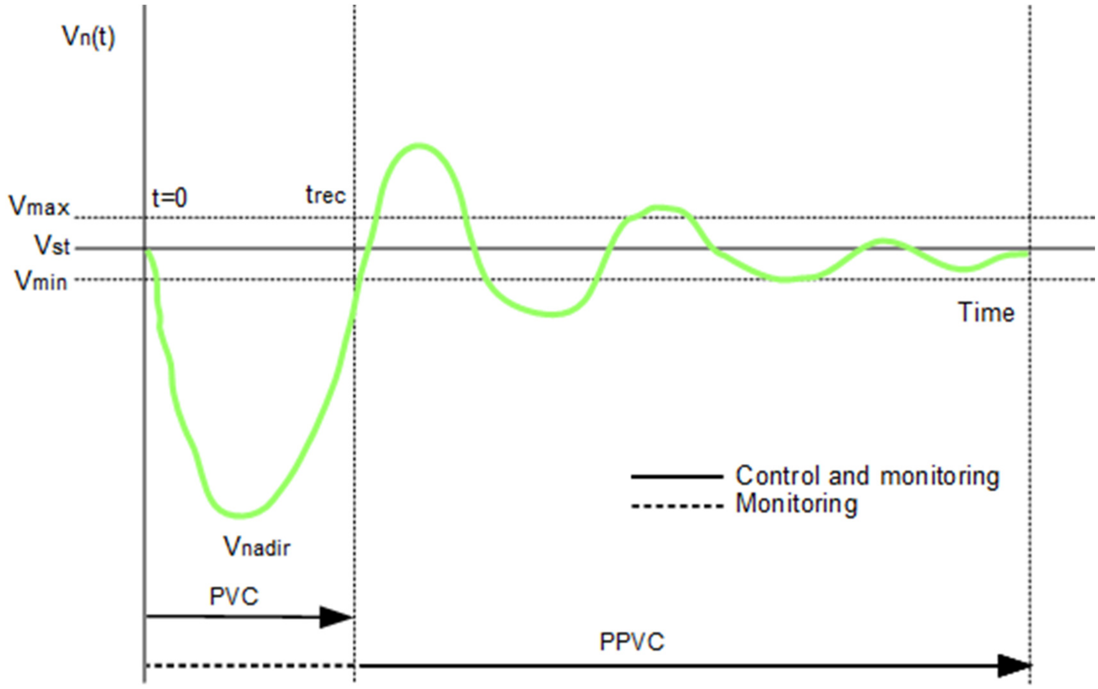

Figure 19: Evolution of rms voltage profile and voltage control domain.

Figure 20 shows the operation of the voltage control mechanisms in a simple system of 4 interconnected Cells, where the application of the subsequent control stages (PVC+PPVC) will be deployed.The goal is to show, in a simplified way, the interactions as a result of the coordination of the Cells' operation in case of an event in one of the Cells, in this case named as CC_i. CC_j, CC_k, and CC_m represent three neighbouring Cells electrically connected to CC_i through one or several tie-lines. The exchange of reactive power between neighbouring Cells has been notated with the initial and the final letter of the Cells that join. This way, Qij will represent the reactive power flow between the Cells i and j. As the purpose of this section is to show a general example of the operation mechanisms, the direction of the reactive power flow is not indicated by the order of the letters in the subscripts. Figure 20 a) displays the initial state of the Web-of-Cells, initially operating at a balance state, corresponding to the schedules and with the voltages in the nodes according to the set-points defined by the Cell Operator. The reactive power flows in the tie-lines interconnecting the Cells are established to maintain the safe and reliable operation. Those reactive power flows in the lines are assumed to have been previously fixed (a range or a maximum value) by agreement of neighbouring Cell operators due to technical or market considerations The voltages in the nodes (Vst) are settled to the values resulting from the last optimal power flow accomplished in the system (state 0). The reactive power flows in the tie-lines can be (ideally) zero or be determined at a value previously agreed with neighbouring Cell operators. It has to be highlighted that, in this example, the reactive power flows only have been considered, but the voltage control at medium or low voltage levels can also be controlled by means of the active power flows. At $t = 0$, a deviation over the voltage set point in one of the nodes of the system is detected (V, Figure 20a)), triggering the activation of the primary voltage control mechanisms. During those first moments after the event (in the order of milliseconds), the primary voltage control of the AVR-type units tries to contain the voltage drop and to stabilize the voltage in order to avoid a voltage collapse. This means that in Figure 20b) a steady point is reached but out of the optimal for both the voltage levels in the nodes and the reactive power flows in the tie-lines. The AVRs action is very fast, so the time gap between the command signals sent to the primary controllers and the effective activation of the voltage regulators can be considered negligible. As a consequence of the disturbance, the power flows between CCi and its neighbours are also altered. The PPVC of the Cells enters into force at time t_{rec}, and by the resolution of the optimal power flow considering the restrictions imposed by the tie lines, the PPVC control determines the new optimal voltage set points (and active power set-points if necessary, in LV networks for example) and the novel flow exchanges by the tie-lines (state 1). After the operation of the devices with PPVC control, the new equilibrium defined by the state 1 is reached.

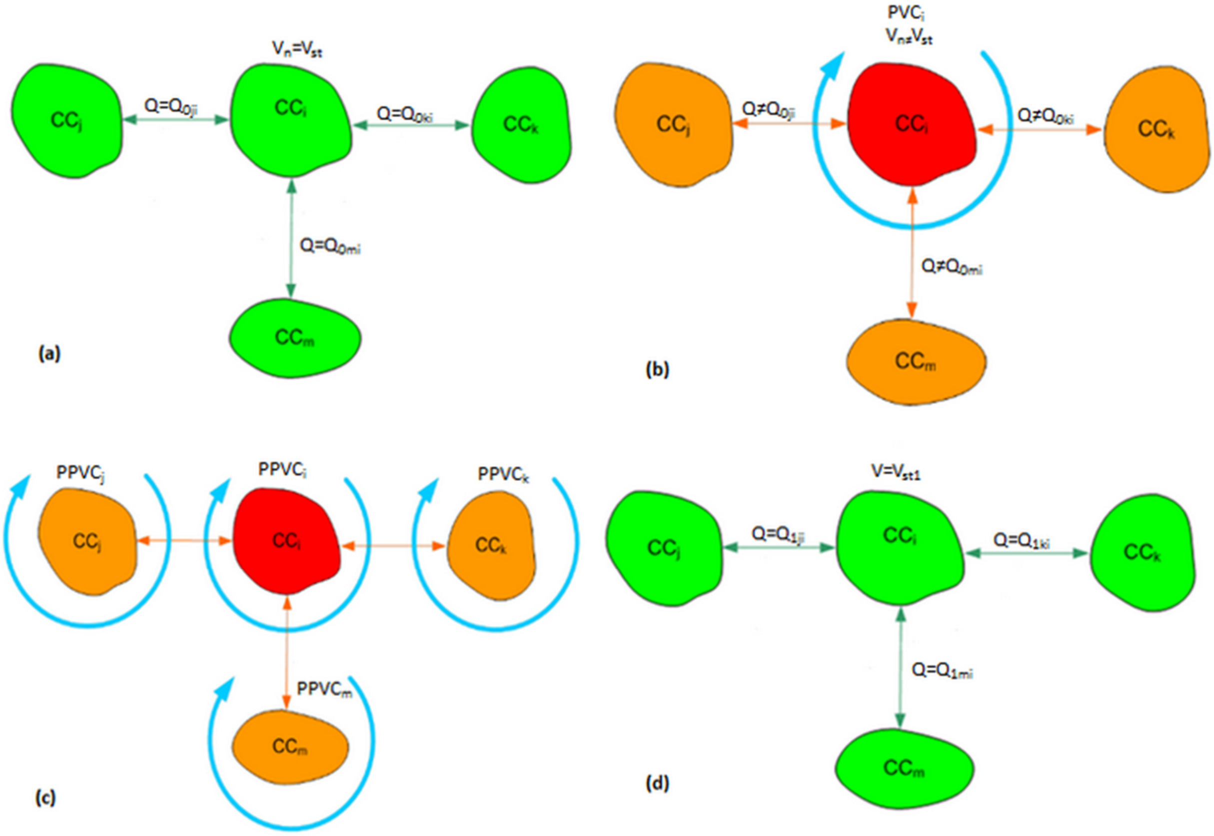

Figure 20: Example of four interconnected cells through various operation and Voltage Control stages.

Depending on the characteristics of the Cells as well as their voltage levels, the voltage deviation can be partially compensated by the operation of devices with active power regulation in primary voltage control acting times, such as the inverter-based devices, the flexible loads or the energy storage systems. This is the reason why, for the voltage control, there is not an inverse relationship between the voltage drop and the increment/decrement of reactive power circulating through the tie-lines, because active and reactive power can be coupled magnitudes.

2.4.2 Methodology - Sub-Task 5.2.1.Identify needed Control Triples from Use Cases

The previous high-level description of the control mechanisms of the Voltage Control Use Cases is used again as the basis for identifying the needed control triples considered in ELECTRA. In this process, several basic control block diagrams can be deduced, which will be elaborated in other Tasks. In Task 5.2 the diagrams will serve to extract the “control aims”, the “observables” towards those aims and the “system input signals” required for the system to appropriately respond to the controller actions. These diagrams are explained for the PVC (distinguishing the different technologies that can be employed) and PPVC use cases in Chapter 5.

2.4.2.1 Definition of Observables needed

By means of the basic control diagrams derived from the control aims analysis it is possible to identify which physical or other quantities are necessary as input signals for each controller. These observables will be obtained by actual measurements of voltages/currents at specific points of the cell in the Web-of-Cells using certain calculation blocks. Each observable for each control loop constitutes the real signal which is normally compared with a reference value to get an appropriate set-point to be followed by a resource participating in control (PVC use cases); a simple example of such a set-point can be a reactive power set-point for a DER unit, in case of PVC. In the case of the PPVC, the comparison with a reference value is not so clear since the observable (after some additional processing) is used within an optimization algorithm (OPF) to obtain the optimal control action. Chapter 5 presents the involved observables per use case and control scheme.

2.4.2.2 Known Control Triples

After having identified the “control aims”, the basic control schemes and the needed “observables”, the last step in the process involves the identification of the “system input signal”, needed for the identification of the “control triples”. The system input signal is the physical quantity which is regulated in order for the system to behave as determined by the control loop, and clearly has an effect on the observable. In general the “system” is the Web-of-Cells, but can be reduced to a cell level for the Voltage Control Use Cases. The first analysis of the control triples for the Voltage control use cases was performed in the frame of T5.1. Known control triples are specified in D5.1 [3] for the primary, secondary and tertiary voltage control, which will be further refined and developed and where necessary modified in this Task T5.2 for the proposed PVC and PPVC.

2.4.2.3 New Control Triples

The analysis carried out in T5.1 must be extended and where necessary adapted from the former primary, secondary and tertiary voltage control to the new PVC and PPVC mechanisms activated under the Web-of-Cells architecture and described in section 2.4. In addition, T6.2 provides a classification of the control schemes according to control topology levels (CTL) and control time scales (CTS), which must be considered during the identification of new control triples (to keep coherence in the ELECTRA developments and the alignment of the activities):

- CTL0: single physical device level
- CTL1: aggregated flexible resource level
- CTL2: cell level
- CTL3: inter-cell level

- CTS0: system response (5 s)
- CTS1: primary level (30 s)
- CTS2: secondary level (120 s)
- CTS3: tertiary level (900 s)

The resulting New Control Triples must be very specific so that there are no ambiguities with regard to selecting, implementing and testing each of them (considering also the implications for WP6).

2.4.3 Methodology - Sub-Task 5.2.2.Determination methods for specific observables

2.4.3.1 Algorithms

In the Spreadsheet "Use Cases-Control Triples" Tab:"WP5 Observable Algorithms" [18] , the observables for the Use Case of Post Primary Voltage Control (PPVC) in the Web-of-Cells are:

- Collection (vector) of apparent power [VA]
- Collection (vector) of voltage phasors [V, rad]

These vectors are input to a State Estimator in order to find an optimised solution for the set-points of node voltages and branch apparent powers, all in complex form. This requires the definition of objective functions to be minimised, e.g. power dissipation by reactive current. Several forms of these functions are to be investigated, in order to arrive at an unambiguous formulation that will apply in most cases in the Web-of-Cells.

In case these objective functions have definite relations to the vectors mentioned above, these may be defined as observables themselves. However this is not the case when values depend on predictions, thereby making the outcome explicitly dependent on time instead of past measured values alone.

The Primary Voltage Control (PVC) has not been considered here since not disruptive changes are expected from current practices.

2.4.3.2 Determination methods for specific observables

These vectors of powers and voltages require many measurements at grid nodes and between nodes. Next these vectors are to be processed by a State Estimator (SE) and/or an Optimal Power Flow (OPF) solver. Although the objective functions for the OPF can be modelled on the basis of a (partially known) grid model, these functions also can be measured directly. This would require measurement of voltage in every node, and a measurement of complex power in every branch between nodes. Next the dissipation due to reactive currents may be calculated for the whole system, and minimised dynamically in the control loop, thereby making State Estimation unnecessary.

2.4.3.3 Measurements

The methodology for the measurements in Voltage Control here is similar to that described for Balance Control in paragraph 2.3.3.3. Measurements.

The methodology consists in measuring the current and the voltage by means of measurement transformers. An A/D converter and a data acquisition process sample the analog input signals – voltage and current – and convert the resulting samples into digital numeric values that will be treated by a Phasor Measurement Unit (PMU). The PMU provides synchronized measurements of real-time phasors for the voltages and the currents.

The sampling frequency could be adapted in function of the control triples, but practically, the Phasor Measurement Units always work with the same sampling frequency, independently of the observables that have to be computed. On the other hand, the algorithms for the observables will use average or cycle values (e.g. 10-cycles average values or 3 seconds average values) depending on the needs for the control triples.

2.4.3.4 *Numerical reliability tests*

For Voltage Control, vectors of many observables, e.g. voltage phasors and reactive power, need to be defined at the same instant of time, if possible. For consistent control, the data needs to be collected efficiently over the grid area considered and transmitted to the controller with a sufficiently small time delay. The influence of errors in recording time due to the failure or absence of a central time reference needs to be small enough to provide a consistent dataset to the controller at all times.

2.4.4 Methodology - Sub-Task 5.2.3.Basic control loop simulation, based on chosen Control Triples

2.4.4.1 *Basic control loop simulation*

The simulation of the basic control loops for the Voltage Control Use Cases within Task T5.2 has a dual purpose: on the one hand, the evaluation of the methods/algorithms that calculate an observable from the measurements in the Web-of-Cells; on the other hand, the analysis of the behaviour of the observable in a closed-loop control and the possible interactions between the algorithm for the calculation of the observable and the control loop itself. With the results obtained by the simulations the suitability of the identified control triples can be assessed. The simulations will be developed for control loops defined for the Voltage Control Use Cases. These basic control loops are also shown in this deliverable in Sections 5.1 and 5.2.

For the final accomplishment of the simulations, we have to define:

- The observables that, based on the measurements, serve as controlled variables
- The controllers for any of the elements that are part of the power system. The inputs that go to the Web-of-Cells from the output of the controllers, taking into account the control topology level.
- The simulation models for representing the elements of the grid with a suitable level of detail. The model should reflect reality but be simple enough in order not to introduce additional uncertainties that could disturb the behaviour of the control loop.

  The Single Reference Power System (SRPS) approach used for providing these simulations models is described in more detail in the chapter 2.2.1.3. Define small test grid in SRPS.

2.4.4.2 *Reliability test*

For the testing of the numerical reliability of the observables the plan is to test the observables identified in Sub-Task 5.2.1 using the basic control loops developed in Sub-Task 5.2.3. The algorithms used for calculating the observables will be provided in the current Sub-Task (5.2.2)

The reliability test will be performed as a sensitivity analysis on various parameters that can influence the observables ability to perform in the control loop. In the analysis we will investigate the relative change in output of the controller due to a small change in relevant parameters and how much a parameter can be changed before the control loop becomes unstable.

The parameters that will be investigated are:

- Noise on the input to the observable algorithm
- Noise on the output of the observable algorithm
- Time delay from the measurement to the observable algorithm
- Time delay from the observable algorithm to the controller

- Tuning parameters of the observable algorithm
- Lack of synchronisation of the voltages/currents measured in the different nodes of a cell (for the PPVC control mechanism)
- Network model errors (for the PPVC mechanism)

In some cases it may also be interesting to test the algorithm on different controllers and different devices if the same observable can be used for different controllers or devices.

2.4.5 Methodology - Sub-Task 5.2.4.Hardware test (lab table)

2.4.5.1 Lab table programmable unit test to be transferred to WP7

Unit tests for the hardware tests will be defined the same way as it is described in Chapter 2.3.5.1. Lab table programmable unit test to be transferred to WP7

3 Selection of Observables for the Main Use Cases

The main Use Cases in the ELECTRA project have been defined in Deliverable D3.1 [2], and are listed in the next table:

Table 5: Main Use Cases in ELECTRA

Control Type	UC abbreviation	Use Case
Balance Control	B1.IRPC	B1-Inertia Response Power Control
	B2.FCC	B2-Frequency Containment Control
	B3.BRC	B3-Balance Restoration Control
	B4.BSC	B4-Balance Steering Control
Voltage Control	T1.PVC	T1-Primary Voltage Control
	T2.PPVC	T2-Post-Primary Voltage Control

For each of the main Use Cases, the Control Triples selected for the Control Time Scales and Control Topology Levels are given in the next paragraphs. Next, a selection of not regularly used Control Triples is made for further definition of the observable algorithms, thereby forming Control Quadruples.

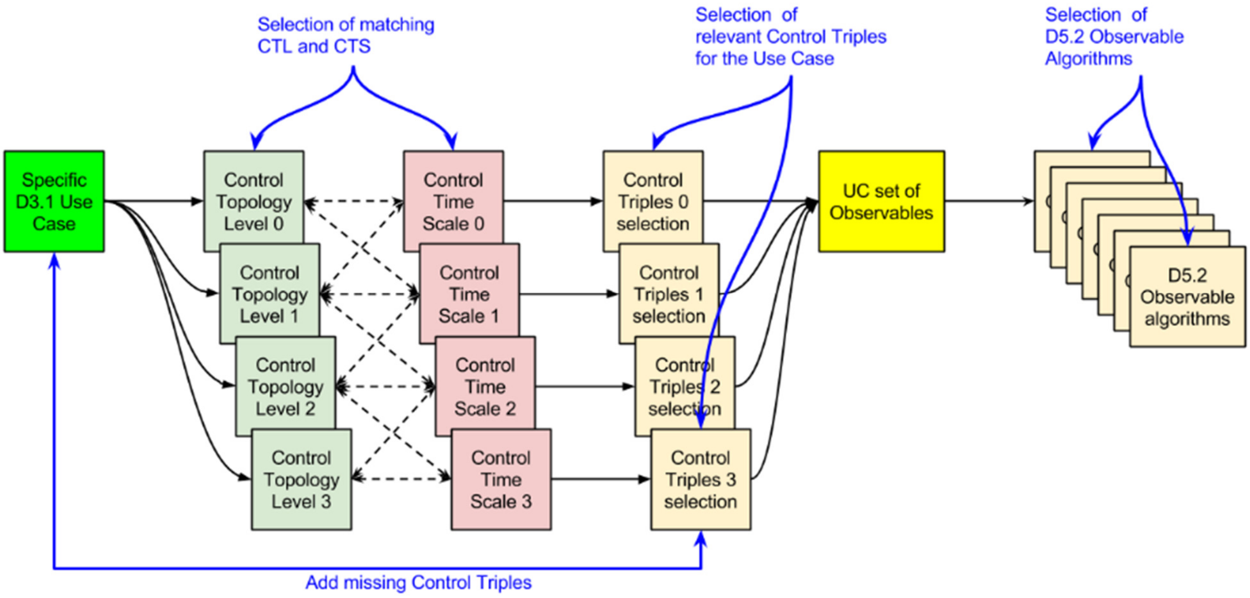

Figure 21: D5.2 Workflow - Observable Selection

3.1 Control Triples for Balance Control

The Control Triples serving the main Use Cases for Balance Control are summarised in the next table. For the actual status see the spreadsheet "Use Cases-Control Triples" Tab:"WP5 Control Triples " [18].

Table 6: Control Triples for Balance Control

Main Use Case	Control Aim	Observable	System Input Signal
B1- Inertia Response Power Control	Inertia Steering at Cell level [s]	Actual Cell Inertia time constant [s]	Deployment of a collection of slow starting Cell resources which exchange inertial response power [0/1] Deployment of inertial response power in a collection of converter interfaced resources [0/1]
	Inertia Steering at Synchronous Area level [s]	Actual Synchronous Area inertia [s]	Deployment of a collection of slow starting Cell resources which exchange inertial response power [0/1] Deployment of inertial response power in a collection of converter interfaced resources [0/1]
	Inertial Response Power Dynamic Control [s]	Inertial time constant of DER [s]	Inertial response power [W]
	Minimise stationary frequency fluctuations [Hz/s]	Actual frequency of node voltage [Hz]	Inertial response power [W]
	Secure transient frequency stability [Hz]	Actual frequency of node voltage [Hz]	Inertial response power [W]
B2- Frequency Containment Control	Minimise frequency deviations [Hz]	Frequency [Hz]	Active Power of aggregated resources [W]
	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]	Actual Network Power Frequency Characteristic (λi) [W/Hz]	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
		Cell Energy production in standard time interval [Ws]	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
		Web-of-Cells Energy production in standard time interval [Ws]	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
B3- Balance Restoration Control	Achieve a minimum of Reserve Capacity [W]	Availability of Flexible Resources [W]	Aggregated active power capacity [W]
	Bring frequency back to its set point [Hz]	Frequency [Hz]	Activation of Active Power of aggregated resources [W]
	Bring frequency back to	Frequency [Hz]	Activation of Active Power of

Main Use Case	Control Aim	Observable	System Input Signal
	its set point in a dynamically optimal way [Hz]		aggregated resources [W]
	Secure dynamically optimal power balance via aggregated resources [W]	Cell power balance [W]	Activation of Active Power of aggregated resources [W]
	Secure Power Balance by aggregated resources [W]	Cell power balance [W]	Activation of Active Power of aggregated resources [W]
B4- Balance Steering Control	Achieve a minimum of Reserve Capacity [W]	Availability of Flexible Resources [W]	Aggregated active power capacity [W]
	Maximise Operation & Maintenance efficiency of aggregated resources [1]	Operation & Maintenance efficiency of aggregated resources [1]	Deployment of Active Power of aggregated resources [W]
	Mitigate imminent Imbalances [W]	Active power of aggregated resources [W]	Deployment of Active Power of aggregated resources [W]
	Substitute aggregated reserves [W]	Active power of aggregated resources [W]	Deployment of Active Power of aggregated resources [W]

3.2 Control Triples for Voltage Control

The Control Triples serving the main Use Cases for Voltage Control are summarised in the next table. For the actual status see the spreadsheet "Use Cases-Control Triples" Tab:"WP5 Control Triples " [18]

Table 7: Control Triples for Voltage Control

Main Use Case	Control Aim	Observable	System Input Signal
T1- Primary Voltage Control	Minimise transient voltage deviations [V]	Actual node voltage [V]	Active power of Synchronous Generator [W] Active power of the controllable loads [W] complex power of aggregated resources (microgrids, VPPs...) [VA] Fast storage active and reactive power [VA] Reactive power of FACTS [VAr] Reactive power of synchronous generator/compensator [VAr]
		Current in DQO axis [A]	complex power of non-rotating generators [VA]
		Voltage in DQO axis [V]	complex power of non-rotating generators [VA]
T2- Post-Primary Voltage Control	Proactive over/undervoltages mitigation [V]	Collection (vector) of complex power	Active power set-points to DERs [W]

Main Use Case	Control Aim	Observable	System Input Signal
		[VA]	Optimal voltage set-points to DERs [V]
		Collection (vector) of voltage phasors [V,rad]	Active power set-points to DERs [W] Optimal voltage set-points to DERs [V]
	Restore voltage levels to pre-incident values while optimizing reactive power flows [V]	Collection (vector) of complex power [VA]	Active power set-points to DERs [W] Optimal voltage set-points to DERs [V]
		Collection (vector) of voltage phasors [V,rad]	Active power set-points to DERs [W] Optimal voltage set-points to DERs [V]

3.3 Resulting observables and their algorithms for Balance Control

The resulting Observables and their Algorithms serving the main Use Cases for Balance Control are summarised in the next table. For the actual status see the spreadsheet "Use Cases-Control Triples" Tab:"WP5 Obs.Algorithms-HorVert " [18] .

Table 8: Resulting observables and their algorithms for Balance Control

Main Use Case	Observable	Observable Algorithm
B1-Inertia Response Power Control	Actual Cell Inertia time constant [s]	Cell level determination of inertial time constant H and NPFC from exponential shape of power transient in tie-line.
	Actual frequency of node voltage [Hz]	1) Dual Second Order Generalised Integrator-Frequency Locked Loop 2) Digital Phase Locked Loop 3) Digital Fourier analysis 4) Three-phase space vector trajectory methods, including use of Clarke and Park transforms 5) Time domain numerical filter
		1) Dual Second Order Generalised Integrator-Frequency Locked Loop 2) Digital Phase Locked Loop 3) Digital Fourier analysis 4) Three-phase space vector trajectory methods, including use of Clarke and Park transforms 5) Time domain numerical filter
	Actual Synchronous Area inertia [s]	Synchronous Area determination of inertial time constant H and NPFC from exponential shape of frequency transient.

Main Use Case	Observable	Observable Algorithm
	Inertial time constant of DER [s]	Device level determination of actual response power from the fluctuations in device power caused by frequency changes.
B2-Frequency Containment Control	Actual Network Power Frequency Characteristic (λi) [W/Hz]	Cell determination of inertial time constant H and NPFC from exponential shape of power transient in tie-line.
	Cell Energy production in standard time interval [Ws]	Moving window integration of tie-line power flows (window time interval e.g. equal to market time interval)
	Frequency [Hz]	1) Zero crossing detection 2) Digital Phase Locked Loop
	Web-of-Cells Energy production in standard time interval [Ws]	Sum over all cells of Cell Energy production in standard time interval [Ws]
B3-Balance Restoration Control	Availability of Flexible Resources [W]	Power profile portfolio of aggregated resources
	Cell power balance [W]	Determine Cell power balance (e.g. Sum of measured tie-line power flows, or SOC deviation of local store.)
	Frequency [Hz]	1) Zero crossing detection 2) Digital Phase Locked Loop
B4-Balance Steering Control	Active power of aggregated resources [W]	Power profile of portfolio of aggregated resources
	Availability of Flexible Resources [W]	Power profile portfolio of aggregated resources
	Operation & Maintenance efficiency of aggregated resources [1]	Operation & Maintenance efficiency function of portfolio of aggregated resources

3.4 Resulting Observables and their algorithms for Voltage Control

The resulting Observables and their Algorithms serving the main Use Cases for Voltage Control are summarised in the next table. For the actual status see the spreadsheet "Use Cases-Control Triples" Tab:"WP5 Obs.Algorithms-HorVert " [18] .

Table 9: Resulting Observables and their algorithms for Voltage Control

Main Use Case	Observable	Observable Algorithm
T1-Primary Voltage Control	Actual node voltage [V]	Moving window Root-Mean-Square (RMS) from sampled actual sine wave voltage.
		Park transformation
	Current in DQO axis [A]	Park transformation
	Voltage in DQO axis [V]	Park transformation
T2-Post-Primary Voltage Control	Collection (vector) of complex power [VA]	From the voltage and current waveform measurements: - Voltage phasor calculation (RMS, phase) - Complex power calculation (extraction of active and reactive power if needed)
	Collection (vector) of voltage phasors [V,rad]	From the voltage and current waveform measurements:

Main Use Case	Observable	Observable Algorithm
		- Voltage phasor calculation (RMS, phase) - Complex power calculation (extraction of active and reactive power if needed)
		From the voltage and current waveform measurements: - Voltage phasor calculation (RMS, phase) - Complex power calculation (extraction of active and reactive power if needed)

Observables needed for PPVC (vector of voltage phasors and vector of complex powers) are already calculated from measurements mainly by TSOs to run state estimation and OPF processes at transmission level. This practice will be extended in ELECTRA to the distribution level (cells).

3.5 Selection of Observables for further definition and testing

Now from the previous tables a selection of not regularly used Observables and Observable Algorithms is made. These observable algorithms are to be further defined and tested in Task T5.2.

Table 10: Selection of not regularly used Observables and Observable Algorithms

Main Use Case	Observable	Observable Algorithm
B1-Inertia Response Power Control	Actual Cell Inertia time constant [s]	Cell level determination of inertial time constant H and NPFC from exponential shape of power transient in tie-line.
	Actual frequency of node voltage [Hz]	1) Dual Second Order Generalised Integrator-Frequency Locked Loop 2) Digital Phase Locked Loop 3) Digital Fourier analysis 4) Three-phase space vector trajectory methods, including use of Clarke and Park transforms 5) Time domain numerical filter
	Actual Synchronous Area inertia [s]	Synchronous Area determination of inertial time constant H and NPFC from exponential shape of frequency transient.
	Inertial time constant of DER [s]	Device level determination of actual response power from the fluctuations in device power caused by frequency changes.
B2-Frequency Containment Control	Actual Network Power Frequency Characteristic (λi) [W/Hz]	Cell determination of inertial time constant H and NPFC from exponential shape of power transient in tie-line.
	Cell Energy production in standard time interval [Ws]	Moving window integration of tie-line power flows (window time interval e.g. equal to market time interval)
	Web-of-Cells Energy production in standard time interval [Ws]	Sum over all cells of Cell Energy production in standard time interval [Ws]
B3-Balance Restoration Control	Availability of Flexible Resources [W]	Power profile portfolio of aggregated resources
	Cell power balance [W]	Determine Cell power balance (e.g. Sum of measured tie-line power flows, or SOC deviation of

		local store.)
B4-Balance Steering Control	Active power of aggregated resources [W]	Power profile of portfolio of aggregated resources
	Availability of Flexible Resources [W]	Power profile portfolio of aggregated resources
	Operation & Maintenance efficiency of aggregated resources [1]	Operation & Maintenance efficiency function of portfolio of aggregated resources

4 Conclusions

The first part of T5.2 "Observables for Distributed Local Control Schemes" concentrated on several activities, which have been documented in the present report:

- Clarification of the scope of Local Control schemes
- More specific stepwise definition of the methodological approach for the whole Task
- Identification of control aims, based on a set of Use Cases (UCs)
- Identification of the needed Control Triples, by using and extending the Control Triples Survey from D5.1 [3]
- Determination methods for specific observables
- The Task continued working on the formal framework in WP5, which was initiated in the preceding T5.1.

The document outlines a methodology specifically created for developing and testing observables for the WoC concept. One of the most important lessons learned in this Task is that development of a radically new concept coined Web-of-Cells for control of the future power system with a high share of RES is a complicated process requiring rethinking of several well-established fundamental principles in the power system domain. In particular, conventional frequency and voltage controls have been reconsidered and the former has been replaced with a more general balance control concept, while the structure of the latter has been modified. These activities have required introduction of several new terms of definitions, which have been proposed in cooperation with WP6. Some of these have been further developed from the previous Tasks, such as Control Time Scales (CTS), while the others are new, such as Control Topology Levels (CTL).

Preparing to the succeeding part of the Task with implementations and testing, a specific part of work was dedicated to the further development of the Single Reference Power System started in T5.1. Among the major novelties are: a demonstration of the SRPS for a simple test network, a structured methodology incorporating the concept of Control Quadruples and Black Box Control Loop description into the Use Case method. Specific algorithms to be investigated for defining new observables have also been determined. In particular the established method for instantaneous reactive power looks promising for the definition of instantaneous frequency.

In a similar manner the concept of Control Triples from T5.1 has been further developed and specific control triples have been identified for the proposed control schemes. This has further materialised into specific observables and algorithms necessary for the definition of these.

The results so far also indicate that the WoC concept together with the above mentioned methodology built on top of the Use Case methodology allow for determining observables for an electric power system supporting future energy systems.

One of the main conclusions is that the conducted work supports the previously launched idea of Web-of-Cells concept, which appears to be viable. Today the Web-of-Cells has evolved from a vague idea in D3.1 into more detailed concept. This leads to WoC dedicated control schemes and priorities, which will allow for solving the local problems locally and thus increasing the overall robustness of power system with high share of RES. This will be more specifically studied and verified in the following implementation part of the Task.

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6 Disclaimer

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Annex: Summary of SRPS candidates

Please find this Annex at the next link:

20151012-ELECTRA-D5.2-Annex: Summary of SRPS candidates

Annex: General Measurements Chain for the currents and voltages by means of Phasor Measurements Units

Please find this Annex at the next link:

20151012-ELECTRA-D5.2-Annex: General Measurements Chain for currents and voltages by means of Phasor Measurements Units

Project No. 609687

FP7-ENERGY-2013-IRP

ELECTRA

European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids

WP 5

Increased Observability

Deliverable 5.2

Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes

<Annex: Summary of SRPS candidates>

20/12/2015

Table of contents

1 Overview

Suitable test grid models, or even whole power system models, must be selected in order to be able to represent the theoretical as well as the empirical developments coming from the ELECTRA project. The election of a common power system model to avoid contradicting of obsolete information in reporting formats or software implementations is essential to guarantee the interoperability of the results obtained by the partners. This common power system model receives the name of Single Reference Power System (SRPS). The SRPS presents as the main advantage the implementation of the power system as power simulation software independent. In this way, the partners are allowed to use the software packages they are more comfortable with. To get extra information about the definition and objectives of the SRPS in ELECTRA, see deliverable D5.1 [3]

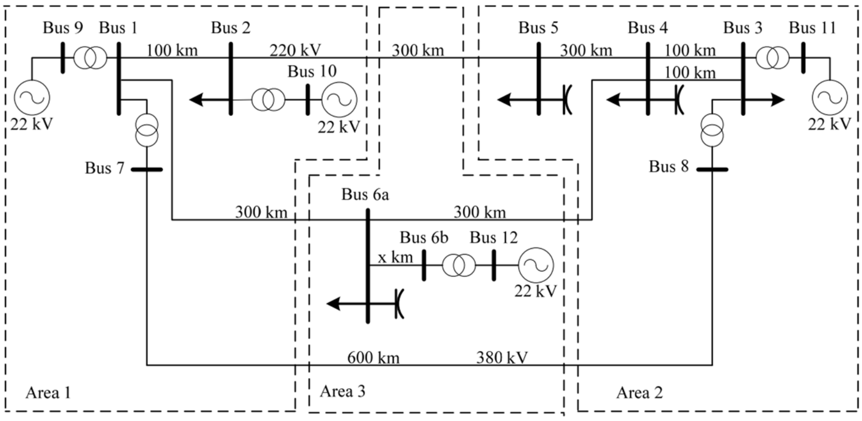
As mentioned in section 2.2.1.2, SRPS candidates have been identified by means of a survey distributed among partners. This second survey was trying to pick up all the relevant information about known test grids and test grids repositories to be analysed in ELECTRA for building the SRPS concept.
In the next sections, the main characteristics about the single test grids (14) or repositories (5) assembled from the survey is summarized and presented by using a common template.

2 Single test grids

2.1 NH-Grid

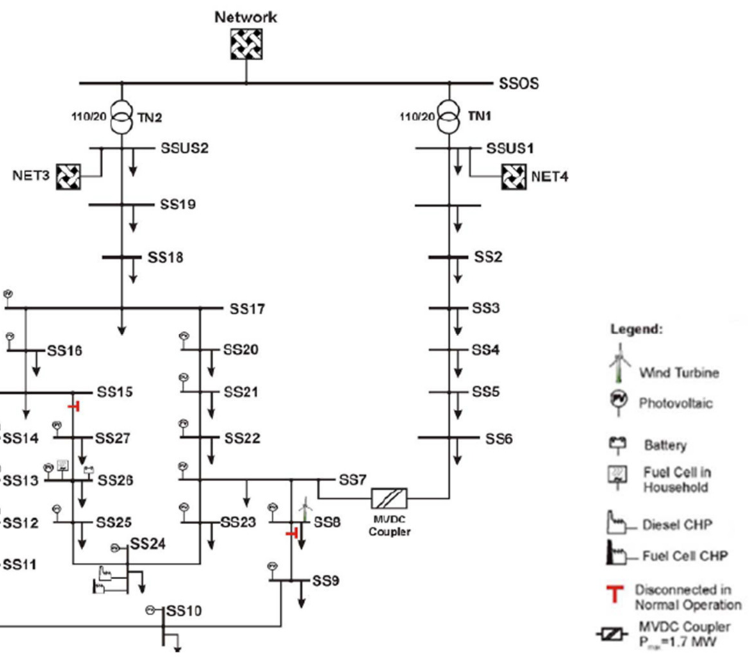
Identifier	NH-Grid
Data privacy	Restricted
Number of nodes	Variable (ten thousands)
Voltage levels	MV & HV
Grid scheme	-
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode • Three-phase unbalanced
DER models available	No
Data format/Software	Simulink/SimPowerSystems

2.2 HV benchmark TN

Identifier	HV benchmark TN
Data privacy	Public
Number of nodes	13
Voltage levels	HV
Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode
DER models available	Yes (Wind, hydro)
Data format/Software	.pdf
Link	http://www.e-cigre.org/Order/select.asp?ID=16639 (free downloadable as CIGRE member)

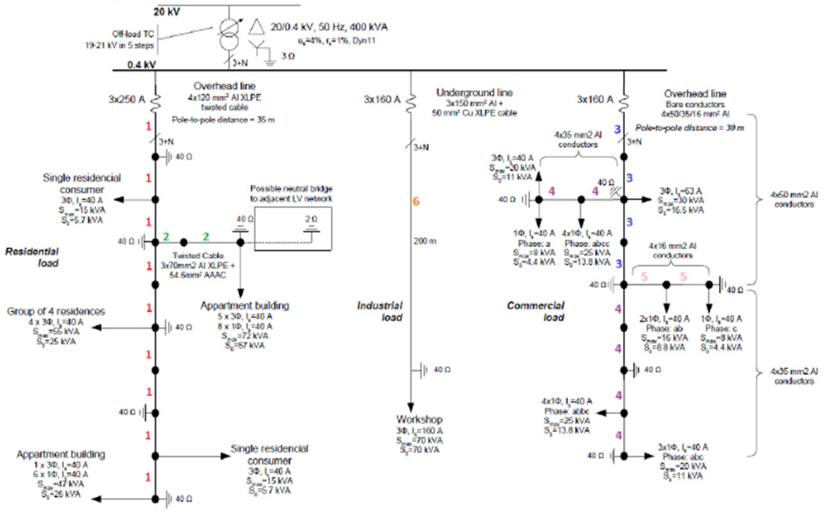
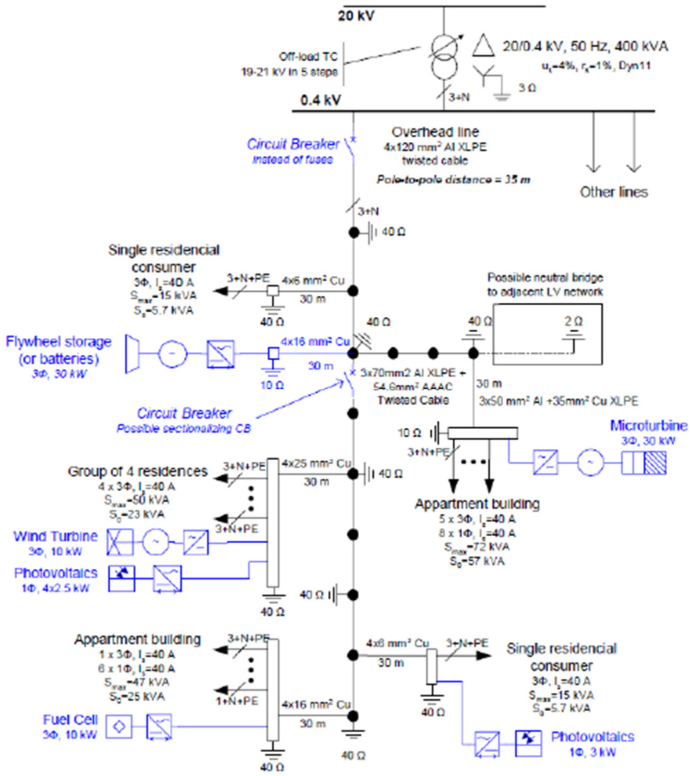
2.3 MV benchmark DN

Identifier	MV benchmark DN
Data privacy	Public
Number of nodes	30
Voltage levels	MV

Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode
DER models available	Yes (Wind, PV, storage and CHP)
Data format/Software	.pdf Google folder: CIGRE MV & LV Grids (Provided by AIT): - PowerFactory - PSSE - SRPS
Link	• Cigre Task Force C6.04, "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources", Report No. 575, April 2014. • http://www.discern.eu/datas/DISCERN_WP6_D6.1_Identification_of_the_scenarios_and_distributed_intelligence.pdf

2.4 LV benchmark DN

Identifier	LV benchmark DN
Data privacy	Public
Number of nodes	2 main buses
Voltage levels	LV

Grid scheme	• LV benchmark / One-line diagram  • Residential feeder with DER resources 
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode • Single-phase • Three-phase unbalanced

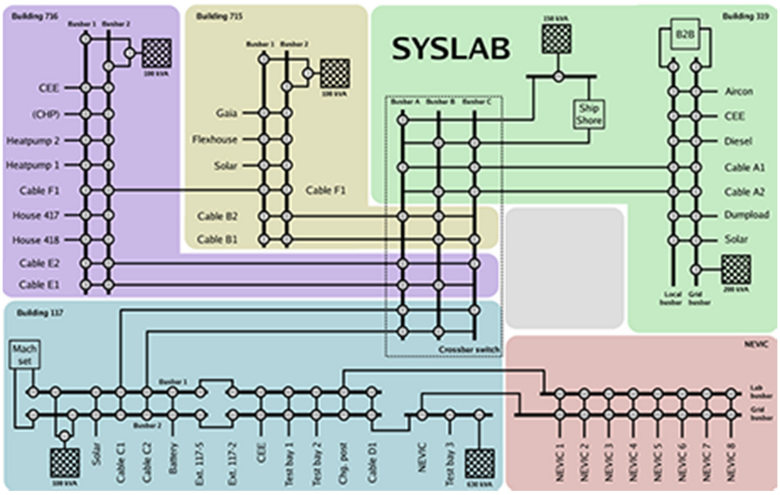
DER models available	Yes (Wind, PV, storage and microturbine)
Data format/Software	.pdf Google folder: CIGRE MV & LV Grids (Provided by AIT): - PowerFactory - PSSE - SRPS
Link	• Cigre Task Force C6.04, "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources", Report No. 575, April 2014. • http://www.discern.eu/datas/DISCERN_WP6_D6.1_Identification_of_the_scenarios_and_distributed_intelligence.pdf

2.5 (IEEE) MV/LV European Reference Grids

Identifier	(IEEE) MV/LV European Reference Grids
Data privacy	Public
Number of nodes	tbd
Voltage levels	MV/LV
Grid scheme	tbd
Steady-state studies based on available data	• Power flow
Transient regime studies based on available data	Limited by used software
DER models available	Yes (small hydro, PV, wind), as negative load (profile-based behaviour of the mentioned DER's; no detailed component models.)
Data format/Software	PowerFactory, PSSE
Link	tbd

2.6 SYSLAB

Identifier	SYSLAB
Data privacy	Restricted
Number of nodes	17
Voltage levels	LV

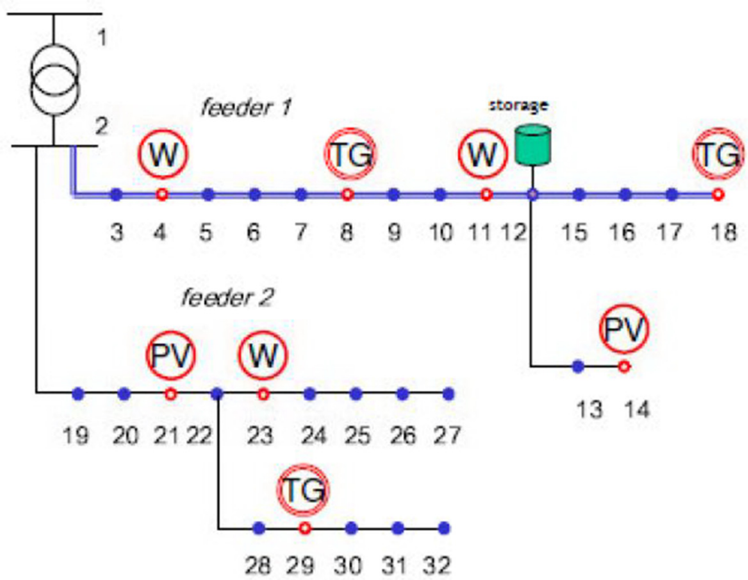
Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Phasor • Single-phase
DER models available	Yes (Wind, PV, storage, diesel, EV and flexible loads)
Data format/Software	PowerFactory
Link	http://www.powerlab.dk/Facilities/SysLab/Technical-Specifications

2.7 CIM IOP

Identifier	CIM IOP
Data privacy	Public
Number of nodes	60 / 100
Voltage levels	HV
Grid scheme	-
Steady-state studies based on available data	• Power flow
Transient regime studies based on available data	-
DER models available	No

Data format/Software	CIM
Link	https://groups.yahoo.com/neo/groups/cimxml

2.8 Nodes

Identifier	32 nodes
Data privacy	Public
Number of nodes	32
Voltage levels	MV
Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients
DER models available	Yes (Wind, PV, storage and microturbine)
Data format/Software	Excel, Matpower, CIM, PowerFactory
Link	http://www.rse-web.it/documenti.page?RSE_originalURI=/documenti/documento/314220&RSE_manipulatePath=yes&country=ita

2.9 FIN_MV_OverheadGrid

Identifier	FIN_MV_OverheadGrid
Data privacy	Restricted
Number of nodes	1
Voltage levels	MV
Grid scheme	-
Steady-state studies based on available data	• Power flow • Short-circuit • Power quality studies
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode • Single-phase • Three-phase unbalanced
DER models available	No
Data format/Software	PSCAD

2.10 FIN_MV_CableGrid

Identifier	FIN_MV_CableGrid
Data privacy	Restricted
Number of nodes	1
Voltage levels	MV
Grid scheme	-
Steady-state studies based on available data	• Power flow • Short-circuit • Power quality studies
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode • Single-phase • Three-phase unbalanced
DER models available	No

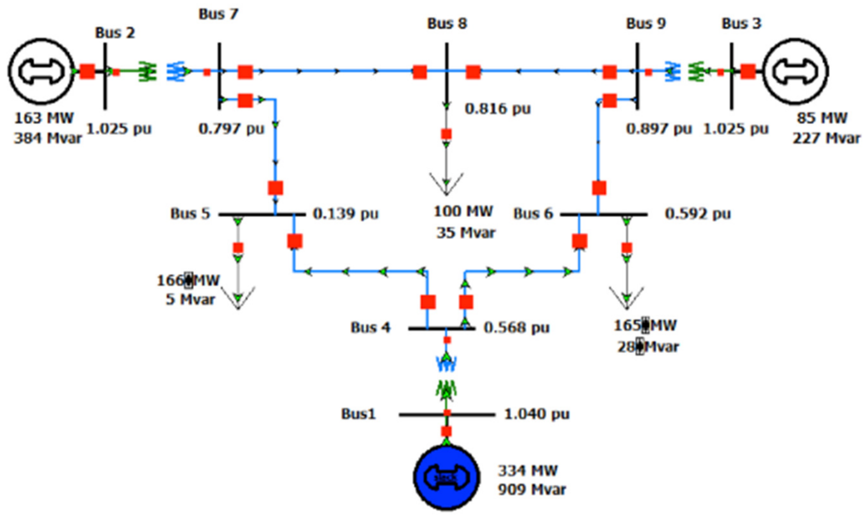
Data format/Software	PSCAD

2.11 FIN_LV_Grid

Identifier	FIN_LV_Grid
Data privacy	Restricted
Number of nodes	2
Voltage levels	LV
Grid scheme	-
Steady-state studies based on available data	• Power flow • Short-circuit • Power quality studies
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Phasor • Continuous mode • Single-phase • Three-phase unbalanced
DER models available	No
Data format/Software	PSCAD

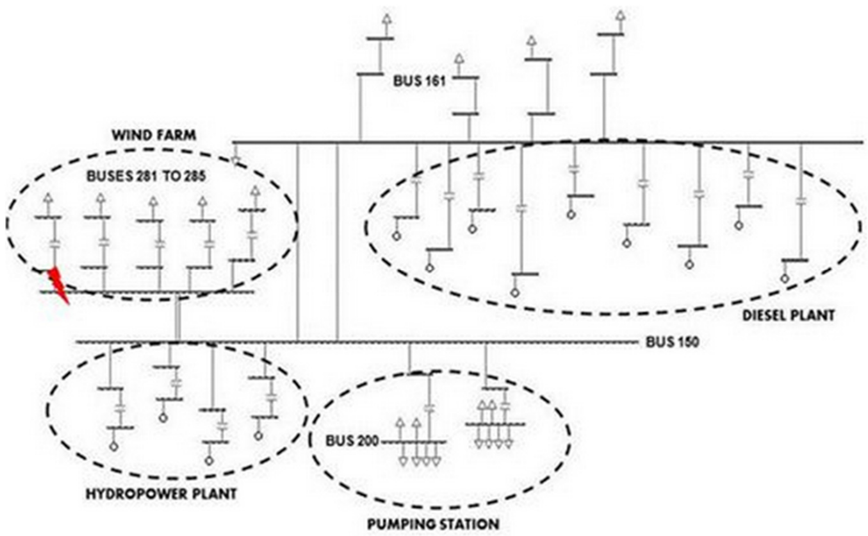
2.12 WSCC_9

Identifier	WSCC_9
Data privacy	Public
Number of nodes	9
Voltage levels	HV/MV/LV

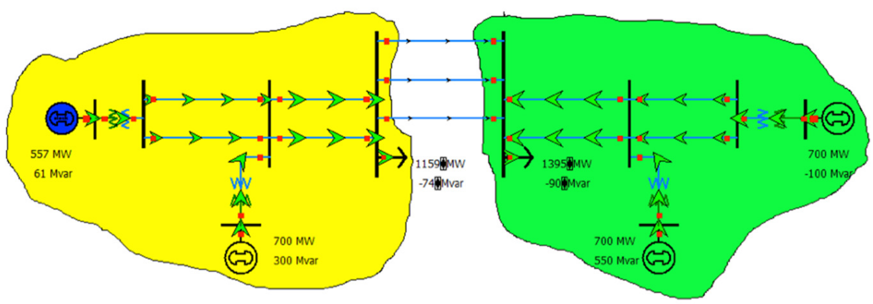
Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients
DER models available	No
Data format/Software	PSS/E (.raw)
Link	http://publish.illinois.edu/smartergrid/wscc-9-bus-system/

2.13 ISOL_grid

Identifier	ISOL_grid
Data privacy	Public
Number of nodes	40
Voltage levels	MV

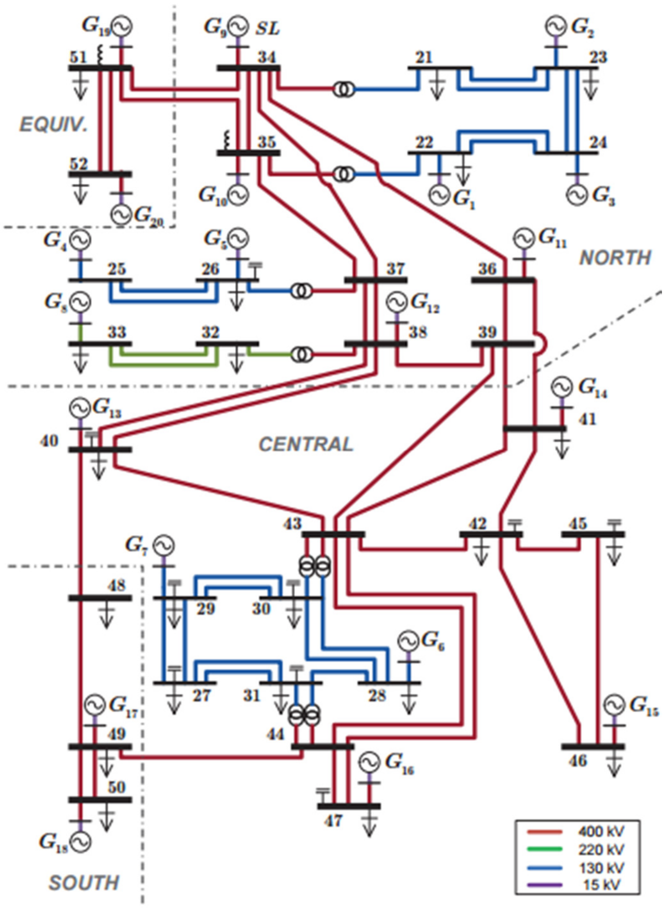
Grid scheme	
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics • Continuous mode
DER models available	Yes (Wind. Hydropower plant, pumped storage)
Data format/Software	PSS/E (.raw, .dyr)
Link	http://www.mdpi.com/1996-1073/5/7/2351

2.14 Two_areas

Identifier	Two_areas
Data privacy	Public
Number of nodes	11
Voltage levels	MV/HV
Grid scheme	
Steady-state	• Power flow

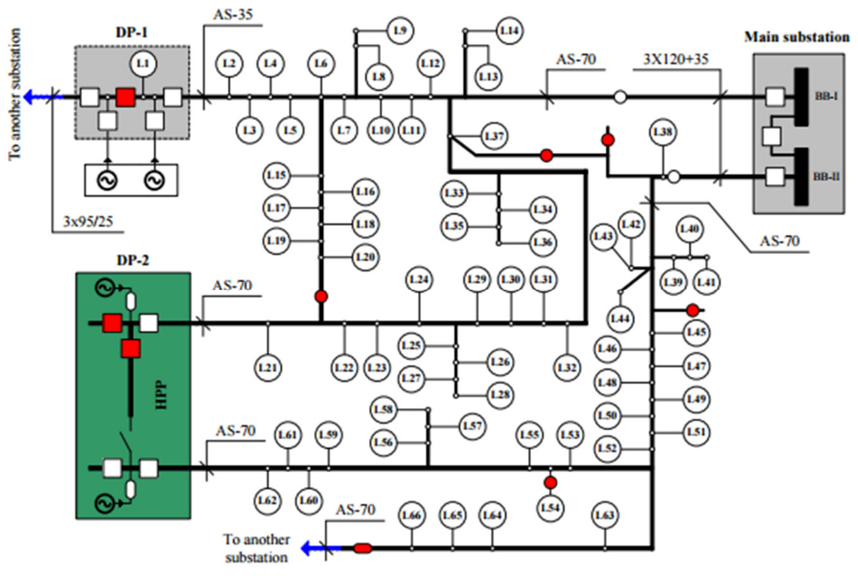
studies based on available data	• Short-circuit
Transient regime studies based on available data	• Slow transients
DER models available	Yes (Wind, PV, storage, diesel, EV and flexible loads)
Data format/Software	PSS/E (.raw), GE PSLF (.epc), PowerWorld (.pwb)
Link	http://publish.illinois.edu/smartergrid/two-area-system/

2.15 Nordic32

Identifier	Nordic32
Data privacy	Public
Number of nodes	32
Voltage levels	MV/HV
Grid scheme	
Steady-state studies based on	• Power flow • Short-circuit

available data	
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics
DER models available	No
Data format/Software	PSS/E (.raw, .dyr), .pdf
Link	http://www.diva-portal.org/smash/get/diva2:609184/FULLTEXT01.pdf

2.16 Grid Annenieki

Identifier	Grid Annenieki
Data privacy	Restricted
Number of nodes	122
Voltage levels	MV
Grid scheme	
Steady-state studies based on available data	• Power flow • Power quality studies
Transient regime studies based on available data	• Slow transients • Continuous mode
DER models available	Yes(Hydropower plant)
Data	MATLAB (.m)

format/Software	
Link	http://energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning%20-%20PSO-projekter/10613%20Final%20report.pdf

3 Repositories

3.1 Gridlab-D

Identifier	Gridlab-D
Data privacy	Public
Number of nodes	50 to 1400
Voltage levels	MV
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	-
DER models available	-
Data format/Software	Gridlab
Link	http://www.gridlabd.org/models/

3.2 IEEE_transmission_static

Identifier	IEEE_transmission_static
Data privacy	Public
Number of nodes	14/24/30/39/57/118/300
Voltage levels	HV
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	-
DER models available	-

Data format/Software	IEEE Common Format
Link	http://www.ee.washington.edu/research/pstca/

3.3 IEEE_transmission_dynamic

Identifier	**IEEE_transmission_dynamic**
Data privacy	Public
Number of nodes	145/162
Voltage levels	HV
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	• Slow transients • Electromechanical • Electromagnetics
DER models available	-
Data format/Software	IEEE Common Format, EPRI format (dynamic data)
Link	http://www.ee.washington.edu/research/pstca/

3.4 IEEE_distribution

Identifier	**IEEE_distribution**
Data privacy	Public
Number of nodes	4/13/34/37/123/8500
Voltage levels	LV/MV
Steady-state studies based on available data	• Power flow • Short-circuit
Transient regime studies based on available data	-
DER models available	-
Data format/Software	Excel, PSCAD
Link	http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html

3.5 EPRI

Identifier	EPRI
Data privacy	Public
Number of nodes	288/1335/2998
Voltage levels	LV/MV
Steady-state studies based on available data	• Power flow • Short-circuit • Power quality studies
Transient regime studies based on available data	-
DER models available	-
Data format/Software	OpenDSS
Link	http://smartgrid.epri.com/SimulationTool.aspx

EERA European Energy Research Alliance Smart Grids Joint Programme

electra Turn On the Grid of the Future

European Commission

Project No. 609687

FP7-ENERGY-2013-IRP

ELECTRA

European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids

WP 5

Increased Observability

Deliverable 5.2

Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes

<Annex: General Measurements Chain for currents and voltages by means of Phasor Measurements Units>

15/10/2015

Table of contents

1 Foreword

Electrical power management requires implementation of data processing units able to monitor networks or equipment and, as applicable, to initiate appropriate control or protection actions. Data sent by current and voltage transformers are processed by protection, control and monitoring units that send signals to operate switchgear and/or information to a supervisory unit or to a central control room. The protection and control plan must specify the operating or non-operating conditions for all the controllers during a contingency and during normal operation (transients). It must indicate the protection and control settings. Hence, it is fundamental to specify properly the characteristics of the measurements chain as a function of the control objectives.

2 Introduction

The observability functions of a network are intended to monitor one or more variables such as currents, voltage, frequency, active and reactive powers, etc. These values are permanently measured and compared with setpoints or thresholds beyond which the situation is defined as abnormal and can lead to instability. When a contingency occurs, controller devices issue signals operating flexible resources.

Permanent monitoring of network electrical values by reliable measurement devices transmitting signals to protection relays and controllers is a key element of the control loops of the Balance and Voltage Control schemes allowing a rapid reaction and the stabilization of the network.

The frequency and the voltage of a MV or HV electrical network are affected by the power imbalance between the production and the loads. It is thus necessary to provide the relevant controllers with the right information to ensure prompt action, as the greater the damage, the longer and more costly the repairs and the heavier the losses.

For all these reasons, the definition of the measurements requires a strict technical specification of the measurement devices. The aim of this document is to provide some basics when defining the measurements chain: current and voltage transformers, analogical to digital conversion and calculation algorithms.

3 General principles of measuring current and voltage

3.1 Introduction

The values of voltage or current in an electrical network are too high to permit convenient direct connection of measuring instruments or relays. Measurement transformers are required to produce a downscaled replica of the input quantity to the accuracy expected for the particular measurement.

Measurement transformers are special types of transformers intended to measure currents and voltages. They are used to supply information to the protective relays and/or current, power and energy metering “instruments”. They must be adapted to network characteristics: voltage, frequency and current. The main tasks of measurement transformers are:

- To transform currents or voltages from a usually high value to a value easy to handle for relays and controllers.
- To insulate the metering circuit from the primary high voltage system.

- To provide possibilities of standardizing the instruments and relays to a few rated currents and voltages.

The performance of measuring transformers during and following large instantaneous changes in the input current or voltage is important, in that this input may depart from the sinusoidal waveform. The deviation may consist of a step change in magnitude, or a transient component that persists for an appreciable period, or both. The instrument transformers and all the measurement chain are required to operate accurately during the period of transient disturbance characterizing the network contingency. An error in the measurements may abnormally delay the operation of the controllers or cause unnecessary operations. So, the functioning and the accuracy of the measurement chain is essential.

3.2 Current transformer

3.2.1 General

Current Transformers (CTs) are used to supply information to the monitoring system and the control relays. For this purpose they must supply a secondary current proportional to the primary current flowing through them and must be adapted to network characteristics: voltage, frequency and current.

They are defined by their ratio, power and accuracy class. Their class (accuracy as a function of CT load and of overcurrent) is chosen according to the application.

A “protection” CT must saturate sufficiently high to allow a relatively accurate measurement of the fault current by the protection whose operating threshold can be very high. Current transformers are thus expected to have an Accuracy Limit Factor (ALF) that is usually fairly high. Note that the associated “relay” must be able to withstand high overcurrents.

An “instrument” or "measurement" CT requires good accuracy around the nominal current value. The metering instruments do not need to withstand currents as high as the protection relays. This is why the “instrument” CTs, unlike the “protection” CTs, have the lowest possible Safety Factor (SF) in order to protect these instruments through earlier saturation.

3.2.2 Measuring of errors

A current transformer is ideally a short-circuited transformer where the secondary terminal voltage is zero and the magnetizing current is negligible. The Figure 1 presents the scheme of an ideal current transformer.

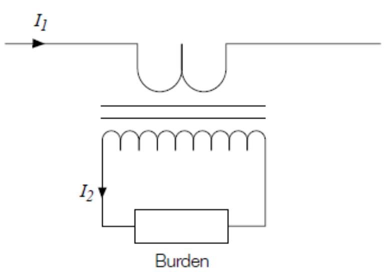


Figure 1: Ideal current transformer.

If the exciting current could be neglected, the transformer should reproduce the primary current without errors and the following equation should apply to the primary and secondary currents:

$$I_2 = \frac{N_1}{N_2} \cdot I_1 \qquad (1)$$

In reality, however, it is not possible to neglect the exciting current. Figure 2 shows a simplified equivalent current transformer diagram converted to the secondary side.

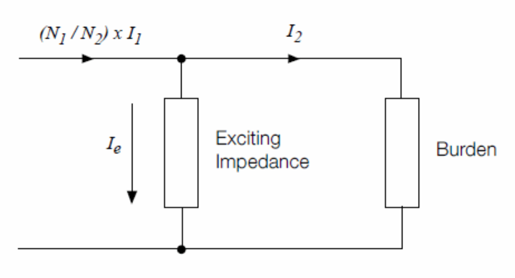


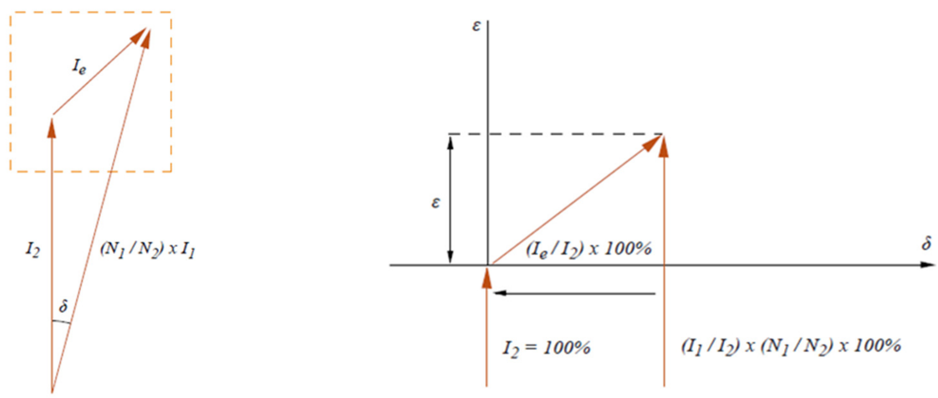
Figure 2: Simplified equivalent schema of a current transformer.

The diagram shows that not all the primary current passes through the secondary circuit. Part of it is consumed by the core, which means that the primary current is not reproduced exactly. The relation between the currents will be in this case:

$$I_2 = \frac{N_1}{N_2} \cdot I_1 - I_e \qquad (2)$$

The error in the reproduction will appear both in amplitude and phase. The error in amplitude is called current or ratio error and the error in phase is called phase error or phase displacement.

The maximum ratio errors (in %) and phase displacement (in min.) are specified by the standard IEC 61689-2, according to the class of the transformer.



(a) (b)

Figure 3: Vector representation of the three currents in the equivalent diagram. (Converted to the secondary side.)

Figure 3 shows a vector representation of the three currents in the equivalent diagram. The right figure shows the area within the dashed lines on an enlarged scale.

In Figure 3b the secondary current has been chosen as the reference vector and given the dimension of 100%. Moreover, a system of coordinates with the axes divided into percent has been constructed with the origin of coordinates on the top of the reference vector. Since δ is a very small angle, the current error ε and the phase error δ could be directly read in percent on the axis (δ = 1% = 1 centiradian = 34.4 minutes).

According to the definition, the current error is positive if the secondary current is too high, and the phase error is positive if the secondary current is leading the primary. Consequently, in Figure 3b, the positive direction will be downwards on the ε axis and to the right on the δ axis.

If we consider all parameters necessary for error calculation, the equivalent diagram in Figure 2 becomes more complex. This is illustrated by the equivalent circuit in Figure 4.

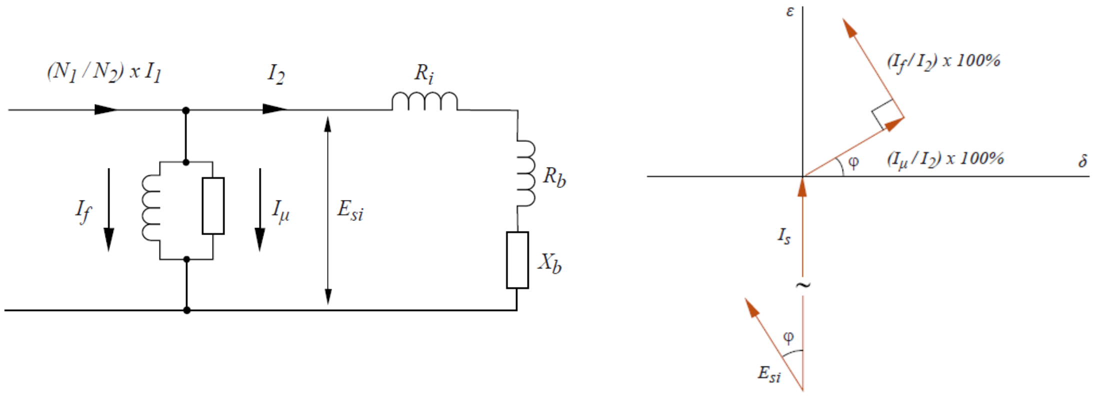


Figure 4: Equivalent schema and vector representation of a current transformer. (Converted to the secondary side.)

The primary internal voltage drop does not affect the exciting current, and the errors — and therefore the primary internal impedance — are not indicated in the diagram. The secondary internal impedance, however, must be taken into account, but only the winding resistance R_i. The leakage reactance is negligible where continuous ring cores and uniformly distributed secondary windings are concerned. The exiting impedance is represented by an inductive reactance in parallel with a resistance. I_μ and I_f are the reactive and loss components of the exiting current.

The vector diagram in Figure 3 is used for determining the errors. The vectors I_μ and I_f, expressed as a percent of the secondary current I_2, are constructed in the diagram shown in Figure 4. The directions of the two vectors are given by the phase angle between the induced voltage vector E_{si} and the reference vector I_2.

$$\varphi = \frac{X_b}{R_b + R_i} \tag{3}$$

where:

R_i is the secondary winding resistance;

R_b and X_b are the resistive and inductive components of the burden.

The reactive component I_μ is 90 degrees out of phase with E_{si} and the loss component I_f is in phase with E_{si}.

3.2.3 Saturation factor

To protect the instruments and meters from being damaged by high currents during fault conditions, a core must be saturated typically between 5 and 20 times the rated current.

The rated Instrument Security Factor (FS) indicates the overcurrent as a multiple of the rated current at which the metering core will saturate. It is thus limiting the secondary current to FS times the rated current. The safety of the metering equipment is greatest when the value of FS is small. Typical FS factors are 5 or 10. It is a maximum value and only valid at rated burden.

In the same way, for a relay core, the saturation voltage is given by the Accuracy Limit Factor (ALF). It indicates the overcurrent as a multiple of the rated primary current up to which the rated accuracy is fulfilled with the rated burden connected. It is given as a minimum value. It can also be defined as the ratio between the saturation voltage and the voltage at rated current. Also the burden on the secondary side influences the ALF.

The next Figure 5 shows that the ratio error decreases when the current increases. This goes on until the current and the flux have reached a value (3) where the core starts to saturate. A further increase of current will result in a rapid increase of the error. At a certain current I_{ps} (4) the error reaches a limit stated in the current transformer standards (IEC 61689-2).

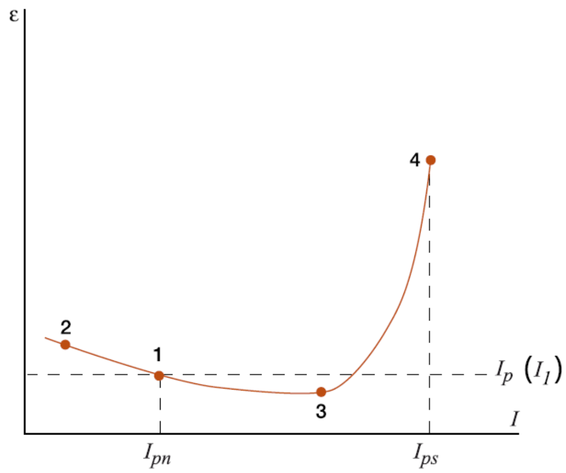


Figure 5: Evolution of the error with the current.

I_{ps} is called the instrument security current for a measuring transformer and accuracy limit current for a protective transformer. The ratio of I_{ps} to the rated primary current I_{pn} defines the Instrument Security Factor (FS) and Accuracy Limit Factor (ALF) for the measuring transformer and the protective transformer respectively. These two saturation factors are practically the same, even if they are determined with different error limits.

One can demonstrate that the saturation factor depends on the magnitude of the burden. This factor must therefore always be related to a certain burden. If the rated saturation factor (the saturation factor at rated burden) is given, the saturation factor for other burdens can be roughly estimated from:

$$FS \ or \ ALF = \frac{I_{ps}}{I_{pn}} \approx (FS_n) \ ALF_n \ . \ \frac{Z_n}{Z} \quad (4)$$

where:

FS_n or ALF_n is the rated saturation factor;

Z_n is the rated burden including secondary winding resistance;

Z is the actual burden including secondary winding resistance.

3.2.4 Burden and accuracy

In practice all current transformer cores should be specially adapted for their application.

The output required from a current transformer depends on the application and the type of load connected to it:

1. Metering equipment or instruments, like kW, kVar, A instruments or kWh or kVArh meters, are measuring under normal load conditions. These metering cores require high accuracy, a low burden (output) and a low saturation voltage. They operate in the range of 5-120% (1-120% S classes, 10-100% IEEE) of rated current according to accuracy classes:
   - 0.2 or 0,2S, 0.5 or 0.5S for IEC;
   - 0.15 or 0.15S, 0.3 or 0.6 for IEEE.

   The next Figure 6 shows the limits for accuracy classes 0.2 and 0.5 according to IEC 61689-2 at different burdens.

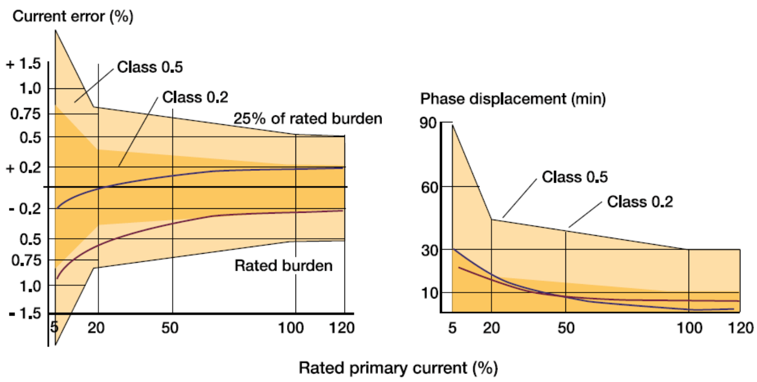


Figure 6: Limits for accuracy classes 0.2 and 0.5 at different burdens.

2. For protection relays and disturbance recorders information about a primary disturbance must be transferred to the secondary side. Measurement at fault conditions in the overcurrent range requires lower accuracy, but a high capability to transform high fault currents to allow protection relays to measure and disconnect the fault. Typical relay classes are 5P, 10P, PR, PX or TP (IEC) or C 100-800 (IEEE).

In each current transformer a number of different cores can be combined. Normally one or two cores are specified for metering purposes and two to four cores for protection purposes.

The next Table 1 gives some examples of accuracy classes according to IEC 61689-2.

Class	For burdens [1]	Limits of errors			Application
		at % rated current	Ratio error %	Phase displacement minutes	
0.1	25-100% of rated burden	5	0.4	15	Laboratory
		20	0.20	8	
		100	0.1	5	
		120	0.1	5	
0.2	25-100% of rated burden <15 VA 1 VA-100%	5	0.75	30	Precision revenue metering
		20	0.35	15	
		100	0.2	10	
		120	0.2	10	
0.2S	25-100% of rated burden <15 VA 1 VA-100%	1	0.75	30	Precision revenue metering
		5	0.35	15	
		20	0.2	10	
		100	0.2	10	
		120	0.2	10	
0.5	25-100% of rated burden	5	1.5	90	Standard commercial metering
		20	0.75	45	
		100	0.5	30	
		120	0.5	30	
0.5S	25-100% of rated burden	1	1.5	90	Precision revenue metering
		5	0.75	45	
		20	0.5	30	
		100	0.5	30	
		120	0.5	30	
1.0	25-100% of rated burden	5	3.0	180	Industrial grade meters
		20	1.5	90	
		100	1.0	60	
		120	1.0	60	
3.0	50-100%	50	3.0	-	Instruments
		120	3.0	-	
5.0	50-100%	50	5.0	-	Instruments
		120	5.0	-	
5P and 5PR [3]	100%	100	1.0	60	Protection
		$ALF \times I_n$	5 [2]	-	
10P and 10PR [3]	100%	100	3.0	-	Protection
		$ALF \times I_n$	10 [2]	-	
PX [4]	E_k, I_e, R_{ct} [5]	-	-	-	Protection

1) PF of secondary burden 0.8 (for 5 VA burden and lower PF = 1.0)
2) Composite error
3) Remanence factor (K_r) shall not exceed 10% after 3 minutes (see section 3.4.3)
4) Rated knee point e.m.f. (E_k). The minimum sinusoidal e.m.f. (r.m.s.) at rated power frequency when applied to the secondary terminals of the transformer, all other terminals being open-circuited, which when increased by 10% causes the r.m.s. excitation current to increase by no more than 50%.
Note! The actual knee point e.m.f. will be ≥ the rated knee point e.m.f.
5) R_{ct} = CTs secondary resistance at 75 °C.

Table 1: Accuracy classes according to IEC 61689-2.

3.2.5 3.2.5. Transients

For special measurement of fault current (transient current,) including both ac and dc components, IEC 61689-2 defines the accuracy classes TPX, TPY and TPZ.

The cores must be designed according to the transient current:

- TPX cores have no requirements for remanence flux and have no air gaps. High remanence CT.
- TPY cores have requirements for remanence flux and are provided with small air gaps. Low remanence CT.
- TPZ cores have specific requirements for phase displacement and the air gaps will be large. Non remanence CT.

If the secondary resistance is adjusted to rated values, the errors shall not exceed the values given in the Table 2 below:

Accuracy class	At rated primary current			Transient error limits under specified duty cycle conditions
	Ratio error	Phase displacement		
	%	Minutes	Centiradians	%
TPX	± 0.5	± 30	± 0.9	$\hat{\varepsilon} = 10$
TPY	± 1.0	± 60	± 1.8	$\hat{\varepsilon} = 10$
TPZ	± 1.0	180 ± 18	5.3 ± 0.6	$\hat{\varepsilon}_{ac} = 10$
				Composite error
5PR	± 1.0	± 60	± 1.8	$\varepsilon_c = 5$
10PR	± 3.0	-	-	$\varepsilon_c = 10$

Table 2: Accuracy classes and error limits for TPX, TPY and TPZ current transformers according to IEC 61869-2.

Selecting the proper CT for some transient conditions is difficult. The current in a distribution feeder changes more often and with greater magnitude than the voltage.

Standard metering-class CTs are generally adequate for frequencies up to 2 kHz (phase error can start to become significant before this limit). For higher frequencies, window type CTs with a high turns ratio (doughnut, split core, bar type, and clamp-on) should be used.

Additional desirable attributes for CTs are:

- a large turns ratio, for example, 2 000:5;
- less than 5 turns in the primary;
- small remanent flux, for example, 10 % of core saturation;
- large core area;
- minimal secondary winding resistance and leakage impedance.

When using a CT to measure transients there are 2 key parameters that need to be considered, current-time product (I□t max) and rise time/droop. Typical values of the rise time (10% to 90%) are in the range of 2 ns to 200 ns. Typical droop values range from 0,1%/µs to 0,5%/ms.

3.3 Voltage transformer

3.3.1 General

The following short introduction to voltage transformers concerns magnetic (inductive) voltage transformers. The content is, however, in general also applicable to capacitor voltage transformers as far as accuracy and measuring errors are concerned.

3.3.2 Measuring errors

Figure 7 shows the scheme of an ideal voltage transformer. If the voltage drops could be neglected, the transformer should reproduce the primary voltage without errors and the following equation should apply to the primary and secondary voltages.

$$U_s = \frac{N_s}{N_p} \cdot U_p \qquad (5)$$

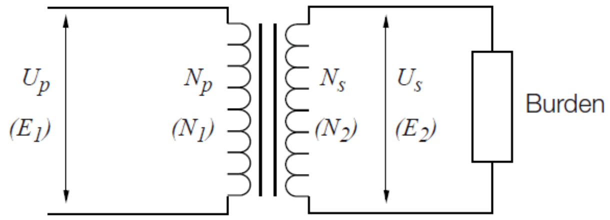


Figure 7: Ideal voltage transformer.

In reality, however, it is not possible to neglect the voltage drops in the winding resistances and the leakage reactances. The primary voltage is therefore not reproduced exactly. The equation between the voltages will be in this case:

$$U_s = \frac{N_s}{N_p} \cdot U_p - \Delta U \tag{6}$$

where:

ΔU is the voltage drop.

The error in the reproduction will appear both in amplitude and phase. The error in amplitude is called voltage error or ratio error, and the error in phase is called phase error or phase displacement.

The maximum ratio deviation (in %) and phase displacement (in min.) are specified by the standard IEC 61689-3, according to the class of the transformer.

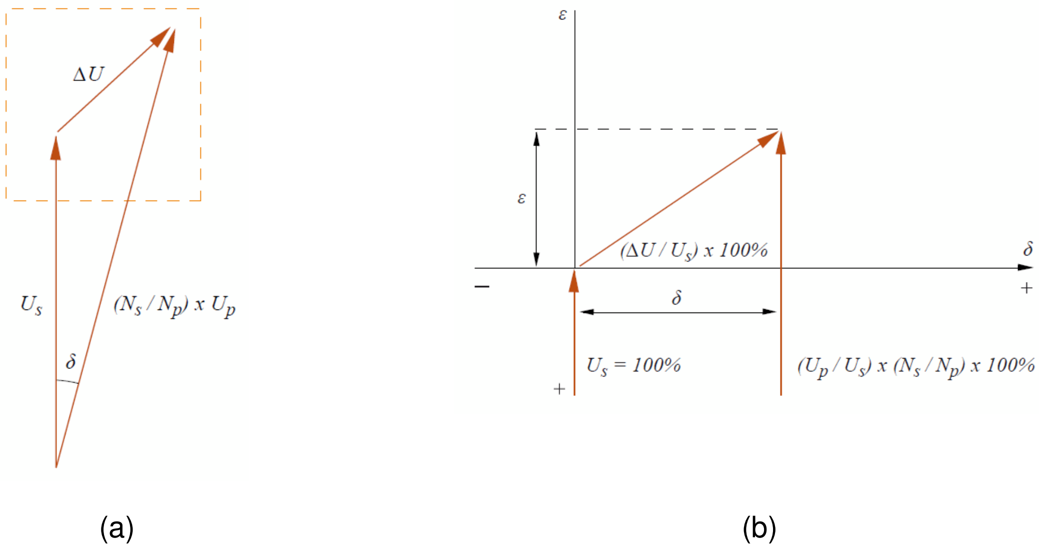


Figure 8: Vector representation of the three voltages in the equivalent diagram. (Converted to the secondary side.)

Figure 8 shows a vector representation of the three voltages in the equivalent diagram (converted to the secondary side.). The right figure shows the area within the dashed lines on an enlarged scale.

In Figure 8b the secondary voltage has been chosen as the reference vector and given the dimension of 100%. Moreover, a system of coordinates with the axis divided into percent has been created with the origin of coordinates on the top of the reference vector. Since δ is a very small angle, the voltage error ε and the phase error δ could be directly read in percent on the axis (δ = 1% = 1 centiradian = 34.4 minutes).

According to the definition, the voltage error is positive if the secondary voltage is too high, and the phase error is positive if the secondary voltage is leading the primary. Consequently, the positive direction will be downwards on the ε axis and to the right on the δ axis.

Figure 9 shows an equivalent voltage transformer diagram converted to the secondary side.

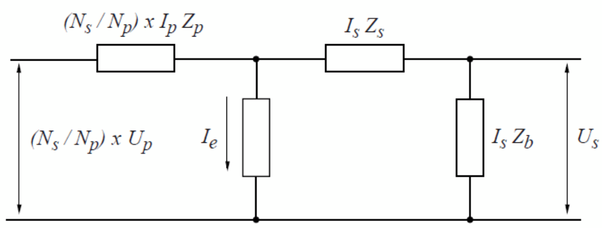
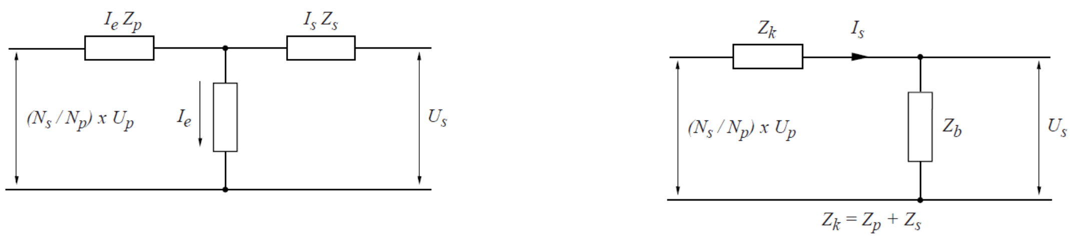


Figure 9: Equivalent schema of a voltage transformer.

The impedance Z_p represents the resistance and leakage reactance of the primary, Z_s represents the corresponding quantities of the secondary. It is practical to look upon the total voltage drop as the sum of a no-load voltage drop caused by I_s. The diagram in Figure 9 is therefore divided into a no-load diagram and a load diagram shown by Figure 10.



(a) (b)

Figure 10: Equivalent schemas of a voltage transformer – (a) no load and (b) load diagram.

The no-load voltage drop is, in general, very small and moreover it is always of the same magnitude for a certain design. For these reasons, the no-load voltage drop can be neglected in these basic calculations. The attention will be turned to Figure 10b and the load voltage drop ΔU_b through Z_k.

$$\Delta U_b = \frac{N_s}{N_p} \, . \, U_p \, . \frac{Z_k}{Z_k + Z_b} = U_s \, . \, \frac{Z_k}{Z_b} \tag{7}$$

The load voltage drop ΔU_b, expressed as a percent of U_s consists of a resistive and a reactive components:

$$\Delta U_r(\%) = \frac{R_k}{Z_b}.100 \quad and \quad \Delta U_x(\%) = \frac{X_k}{Z_b}.100 \qquad (8)$$

The vector diagram in Figure 8 is used for determining the errors. The two vectors ΔU_r and ΔU_x are constructed in the diagram shown by Figure 11.

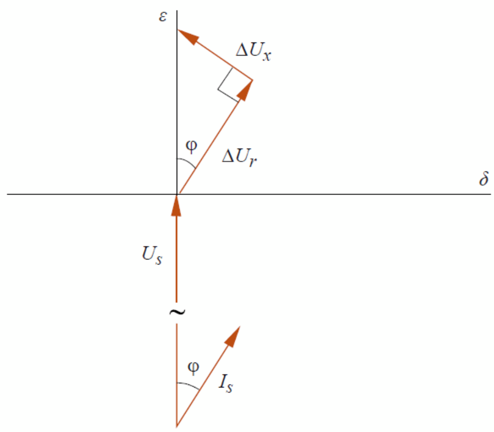


Figure 11: Load vector diagram of the equivalent voltage transformer.

The direction of the two vectors is given by the phase angle between the load current vector I_s and the reference vector U_s.

$$\varphi = atan\frac{X_b}{R_b} \qquad (9)$$

The resistive component ΔU_r is in phase with I_s and the reactive component ΔU_x is 90° out of phase with I_s.

It is worth mentioning that the errors vary if the voltage is changed. This variation depends on the nonlinear characteristic of the excitation curve which means that the variation will appear in the no-load errors. The error contribution from the load current will not be affected at all by a voltage change.

The variation of errors is small even if the voltage varies within wide limits. Typical error curves are shown in Figure 12.

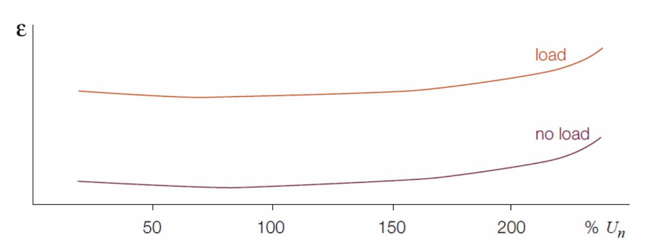


Figure 12: Variation of errors as a function of the voltage.

3.3.3 Accuracy and burden capability

For a certain transformer design, the burden capability depends on the value of the short-circuit impedance. A low value for the short-circuit impedance (a high quantity of copper) means a high burden capability and vice versa. The burden capability must always be referred to a certain accuracy class.

If 200 VA, class 1 is performed with a certain quantity of copper, the class 0.5 capability is 100 VA with the same quantity of copper, on condition that the turns correction is given values adequate to the two classes. The ratio between accuracy class and burden capability is approximately constant. This constant may be called the "accuracy quality factor " K of the winding:

$$K = \frac{100 \,. A}{P} \tag{10}$$

where:

A is the accuracy class;

P is the rated burden in VA.

3.4 Capacitor Voltage Transformer

The capacitor voltage transformer is the most used voltage transformer for high voltages over 145 kV. The application for capacitor voltage transformers (CVTs) is the same as for inductive voltage transformers. In addition to those, the CVT can also be used as a coupling capacitor in combination with power line carrier (PLC) equipment for telecommunication, remote control etc.

The dual function – voltage transformer and coupling capacitor – makes the CVT an economic alternative also for voltages lower than 145 kV.

The CVT consists of two parts, the capacitive voltage divider (CVD) with the two capacitances C_1 and C_2 and the electromagnetic unit (EMU).

The size of the capacitances C_1 and C_2 determines the voltage ratio of the CVD.

The EMU contains an inductive voltage transformer, a tuning reactance and a protection against ferro-resonance.

The basic theory regarding accuracy classes, ratio and phase errors etc is the same for CVTs as for inductive voltage transformers.

The capacitor voltage divider – CVD, contains two series connected capacitors, C_1 and C_2. The voltage divider is loaded by an electromagnetic unit – EMU, which contains sufficient inductance for compensation of the capacitance in the CVD. The compensation inductance is obtained from the transformer windings and from a specially design tuning reactor.

The complete circuit diagram is shown in Figure 13, where the EMU is represented by the primary resistance R_1 and inductance L_1. Corresponding on the secondary side is R_2 and L_2. R_t and L_t are resistance and inductance of the tuning reactor.

The magnetizing impedance is represented by the resistance R_m in parallel with inductance L_m. The losses of the capacitor section are represented by R_{c1} and R_{c2}.

The total series-inductance includes the leakage inductance $L_1 + L_2$ and the tuning inductance L_t.

The impedance Z_b represents the load connected to the secondary terminals. Figure 13 can be converted to an equivalent circuit according to Figure 14.

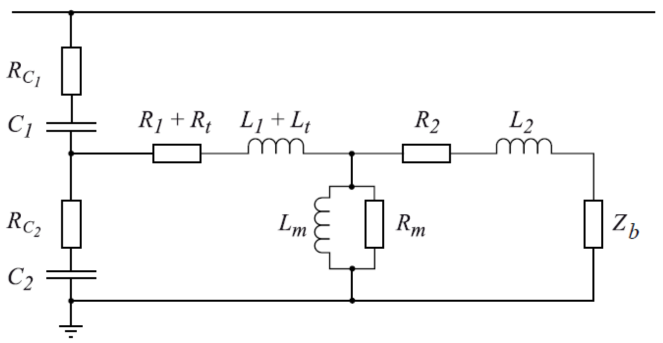


Figure 13: Complete circuit diagram of a capacitor voltage transformer.

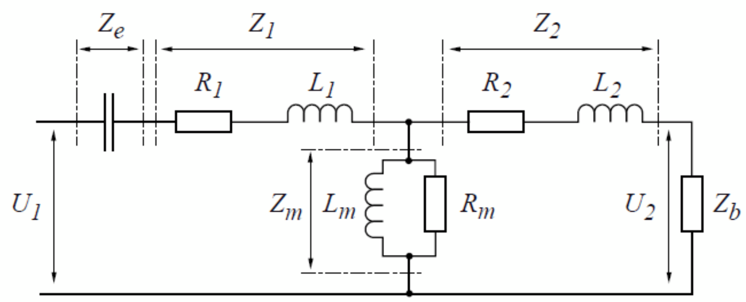


Figure 14: Equivalent circuit of a capacitor voltage transformer.

The ratio of the EMU is defined according to the same rules as for inductive voltage transformers and the total ratio, from high voltage side of CVD to secondary side of EMU is then defined by:

$$n_{tot} = \frac{U}{U_2} = \frac{N_1}{N_2} \cdot \frac{C_1 + C_2}{C_1} \quad (11)$$

This is same as for inductive voltage transformers, the only difference is the capacitance $C_e = C_1 + C_2$, called equivalent capacitance, in series with the primary winding.

3.4.1 Rated voltage factor

Voltage transformers, both inductive and capacitive types are usually connected phase to earth. In the event of a disturbance in a three-phase network, the voltage across the voltage transformer may sometimes be increased even up to the voltage factor, F_V times the nominal rated performance voltage.

IEC specifies the voltage factors F_V:

- 1.9 for systems not being solidly earthed;
- 1.5 for systems with solidly earthed neutral.

The voltage transformer core must not be saturated at the voltage factor.

3.4.2 Measuring errors

The fundamental function of the CVT is resonance between the capacitive and inductive reactance at rated frequency. It can therefore not be expected that the CVT will have the same accuracy for frequencies deviating from the rated.

The IEC 61869-5 standard specifies that for a metering class the accuracy shall be maintained for a frequency variation between 99-101% of rated frequency and for protection class between 96-102%.

The sensitivity for frequency variations is dependent on the equivalent capacitance C_e and the intermediate voltage. High values give a lower sensitivity and smaller variations.

A purely resistive burden will give error variation only for phase displacement and an inductive burden gives variation both in ratio and in phase.

Figure 15 shows an example of frequency variation for the range 49-51 Hz with burdens having cos ϕ = 1 and 0.8 inductive.

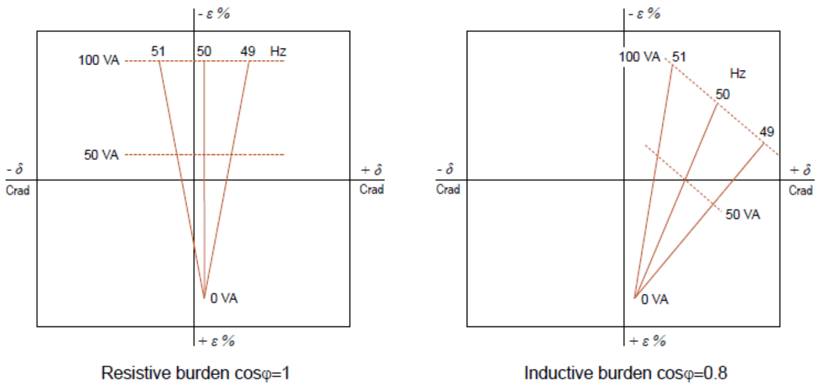


Figure 15: Error variations in ratio and in phase in function of the frequency and the power factor of the burden.

The inclination of the load line, in an error diagram, is changed by the power factor of the burden. Like for an inductive voltage transformer, the load line rotates in the error diagram, clockwise for inductive burdens. By the tuning reactance of the EMU it is possible to adjust the phase displacement to a minimum for rated burden. Other factors, though, must be considered influencing the errors so that the total error complies with the accuracy class.

Like for an inductive voltage transformer, the errors of a CVT change very little for voltage variations. The voltage dependence can for all practical applications be neglected.

The accuracy requirements (IEC) are the same for CVTs as for inductive voltage transformers:

Metering classes according to IEC:

- 80-120% rated voltage;
- 0-100% rated burden (1-10 VA), 25-100% rated burden (≥10 VA).

3.4.3 Quality factor

The performance, like frequency dependence of accuracy, possibility to meet high accuracy at high burdens and the amplitude of the transient response of a CVT can be related to a "quality factor" Q:

$$Q = C_e \,.\, U_1^2 \tag{12}$$

where:

C_e is the equivalent capacitance:

$$C_e = C_1 + C_2 \tag{13}$$

and U_1 is the intermediate voltage at the terminals of the capacitor C_2:

$$U_1 = \frac{U_{nom}}{\sqrt{3}} \cdot \frac{C_1}{C_1 + C_2} \tag{14}$$

The change of phase displacement due to frequency variations can be written:

$$\Delta\delta = \frac{B\,.(X\% + Y\%)}{2\pi f Q} \tag{15}$$

where:

Δδ is the variation of phase displacement;

B is the connected burden in VA;

X is the frequency range in % for the accuracy class in applicable standard:

$$X = \pm\,(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega})\,.\,100\% \tag{16}$$

Y is the step size in % of the tuning reactance;

F is the rated frequency in Hz.

It is seen that a high value of the quality factor Q is essential for keeping the error variations small.

3.4.4 Burden and accuracy

As can be seen from Figure 12 the variation of accuracy within a wide range of voltages is very small. The transformers will therefore supply a secondary voltage at good accuracy even when the primary voltage varies considerably from the rated voltage. A check must, however, be made for the connected metering and relaying equipment, to ensure that they operate satisfactorily at the different voltages.

The normal measuring range of a voltage transformer is for the metering winding 80-120% of the rated voltage. The relay winding has a voltage range from 0.05 to 1.5 (systems with solidly earthed neutral) or 1.9 (systems not being solidly earthed) of the rated voltage.

As for the current transformers the accuracy is divided into classes for measuring and classes for protection purposes. On a voltage transformer provided with more than one secondary winding, these windings are not independent of each other, as in the case of a current transformer with several secondary windings each on their own core. The voltage drop in the primary winding of a voltage transformer is proportional to the total load current in all secondary windings. Measuring and protective circuits can therefore not be selected independently of each other. When the burden consists of metering and relaying components, the higher accuracy class required for metering must be selected.

The Figure 16 gives typical error curves and limits for classes 0.2 and 0.5 according to IEC 61689-3.

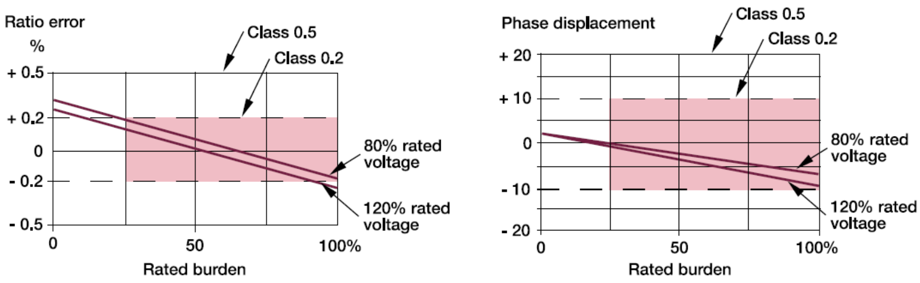


Figure 16: Typical error curves and limits for classes 0.2 and 0.5.

The metering classes of IEC 61689-3 are valid for 80-120% of rated voltage and 0-100% rated burden (1-10 VA), 25-100% rated burden (≥10 VA).

The protective classes are valid from 5% to F_V times rated voltage and for 25-100% of rated burden (F_V is the voltage factor, see above).

The next Table 3 gives some examples of accuracy classes according to IEC 61689-3.

Class	Range		Limits of errors		Application
	Burden %	Voltage %	Ratio %	Phase displacement Minutes	
0.1	25-100 *)	80-120	0.1	5	Laboratory
0.2	25-100 *)	80-120	0.2	10	Precision and revenue metering
0.5	25-100 *)	80-120	0.5	20	Standard revenue metering
1.0	25-100 *)	80-120	1.0	40	Industrial grade meters
3.0	25-100 *)	80-120	3.0	-	Instruments
3P	25-100 *)	5-F_V **)	3.0	120	Protection
6P	25-100 *)	5-F_V **)	6.0	240	Protection

*) For burdens <10 VA, 0 - 100%, PF = 1
**) F_V = Voltage factor

Table 3: Examples of accuracy classes according to IEC 61689-3.

3.5 Transient response

The design with capacitive and inductive elements means that the CVT has more complex transient behaviour than an inductive voltage transformer.

The transient response is the ability of a CVT to reproduce rapid changes of the primary voltage and is defined as the remaining secondary voltage at a specified time after a short-circuit of the primary voltage. The remaining voltage is dependent on design parameters of the CVT, but also on the size and power factor of the connected burden.

It can be shown that a high equivalent capacitance and a high intermediate voltage, and then a high quality factor Q, reduce the transient. High burden gives higher amplitude of the transient than a low burden, inductive power factors also make the transient bigger.

When a primary short-circuit occurs, the discharge of the energy stored in the capacitive and inductive elements of the transformer will result in a transient voltage oscillation on the secondary side. This transient is normally a combination of one low frequency oscillation of 2-15 Hz and one high frequency oscillation that can lie between 900 to 4000 Hz. The high frequency part of this is damped out within short time, normally within 10 ms, whereas the low frequency part lasts longer. The amplitudes of the transient are determined by the phase angle of the primary voltage at the moment of the short-circuit. Higher capacitance of the CVT gives lower amplitude of the low frequency oscillation.

The standard IEC 61689-5 defines limits and classes for the transient response.

3.5.1 Remarks

In an inductive voltage transformer only the fast high frequency oscillation lapse occurs. The dominating low frequency lapse in the capacitor voltage transformer does not occur since there are no capacitors in the inductive voltage transformers.

VTs should be sized to prevent measured disturbances from inducing saturation. For low-frequency transients, this requires that the knee point of the transducer saturation curve be at least 200% of the nominal system voltage.

The frequency response of a standard metering class VT depends on its type and the burden applied. With a high impedance burden, the response is usually adequate to at least 2 kHz, but it can be less.

High-frequency transient measurements require a capacitor divider or pure resistive divider. Special purpose capacitor dividers can be obtained for measurements requiring accurate characterization of transients up to at least 1 MHz.

3.5.2 Ferro-resonance

Ferro-resonance may occur in capacitor voltage transformer as the circuit contains a capacitor and a reactor incorporating an iron core (a non-linear inductance). Ferro-resonance is a potential source of transient overvoltage.

The phenomenon may be started if the core of the intermediate voltage transformer for some reason happens to be saturated, for example during a switching operation. A resonance oscillation, normally having a frequency lower than the normal 50 Hz, may then be initiated and superposed on the normal frequency voltage and may last a long time if it is not efficiently damped.

A ferro-resonance oscillation, which is not damped out efficiently, is dangerous for the transformer. Under such circumstances the core of the intermediate voltage transformer works at full saturation and the excitation current might be large, so that there is a risk of a failure.

When designing the CVT it is therefore essential that such oscillations are avoided. All CVTs are provided with some type of ferro-resonance damping device, to protect the CVT from being damaged by over-voltages or overheated due to core saturation.

3.6 Standards

The measurement transformers are subjected to the recommendations of European Standards (HD, EN) and the Standards of the International Electrotechnical Committee (IEC). In particular, the latest editions of the following documents shall apply:

- Current transformer
  IEC 61689-2 : Current Transformers

IEC 61689-5: Transient response

- Voltage transformers
  IEC 61689-3 : Voltage Transformers

  IEC 61689-5: Transient response

4 Digital measurements

4.1 General

The electrical quantity to be measured may be either directly accessible, as is generally the case in low voltage systems, or accessible via measurement transducers like measurement transformers. These transducers are needed to step down the voltage, to isolate the input circuits from the system voltage, or to transmit the signals over some distance. To accomplish any of these functions, the characteristics of the transducer must be suitable for the variableof interest, the current or the voltage.

The standard IEC 61000-4-30 defines the methods for measurement and interpretation of results for power quality parameters in ac power supply systems with a declared fundamental frequency of 50 Hz or 60 Hz.

Measurement methods are described for each relevant variable in terms that give reliable and repeatable results, regardless of the method's implementation. This standard addresses measurement methods for in-situ measurements.

Measurement of variables covered by IEC 61000-4-30 is limited to conducted phenomena in power systems. The power quality parameters considered in this standard are power frequency, magnitude of the supply voltage, flicker, supply voltage dips and swells, voltage interruptions, transient voltages, supply voltage unbalance, voltage harmonics and interharmonics, mains signalling on the supply voltage, rapid voltage changes, and current measurements.

The whole measurement chain is shown in Figure 17.

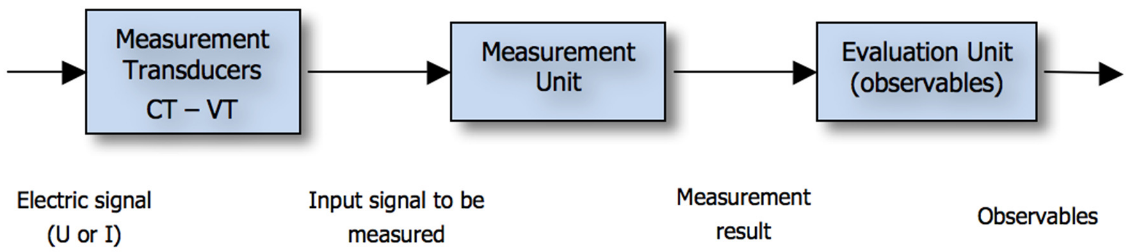


Figure 17: Whole measurement chain.

An "instrument" may include the whole measurement chain (see Figure 17). In the standard IEC 61000-4-30, the normative part does not consider any possible measurement transducers external to the instrument and their associated uncertainty, but Clause A.3 gives guidance.

4.2 Frequency response of transducers

There are two important concerns that should be addressed when selecting transducers for ac mains transients. First, signal levels should use the full scale of the instrument without distorting or clipping the desired signal. Second, the frequency response (both amplitude and phase) of the transducer should be adequate for the expected signal.

4.2.1 Frequency and phase response of voltage transformers

In general, transformer-type electromagnetic voltage transducers have frequency and transient responses suitable up to typically 1 kHz; but the frequency range may sometimes be limited to well below 1 kHz, and sometimes may extend to a few kHz.

Simple capacitor dividers can have frequency and phase responses that are suitable up to hundreds of kHz or even higher; however, in many applications a resonant circuit is intentionally added, making the frequency response of the capacitive divider unsuitable for measurements at any frequency other than the fundamental.

Resistive voltage dividers may have frequency and phase response suitable up to hundreds of kHz. However, they may introduce other problems, for example, the capacitive load of the measurement instrument can influence the frequency and phase response of the resistive voltage dividers.

4.2.2 Frequency and phase response of current transformers

As current transformers are wound electromagnetic devices, the frequency response varies according to the uncertainty class, type (manufacturer), turns ratio, core material and cross section, and the secondary circuit load.

Usually, the cut-off frequency of a current transducer ranges from 1 kHz to a few kHz, and the phase response degrades as the cut-off frequency is approached.

New concepts of current transducers with higher cut-off frequency and better linearity are being developed (optical and Hall-effect transducers).

4.3 Data acquisition

4.3.1 General

Data acquisition is the process of sampling signals that represent measures of physical variables (i.e. voltage and current) and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems typically convert analog waveforms into digital values for processing. The components of data acquisition systems include (Figure 18):

- Sensors that convert physical variables to electrical signals;
- Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values;
- Analog-to-digital converters, which convert conditioned sensor signals to digital values.
-

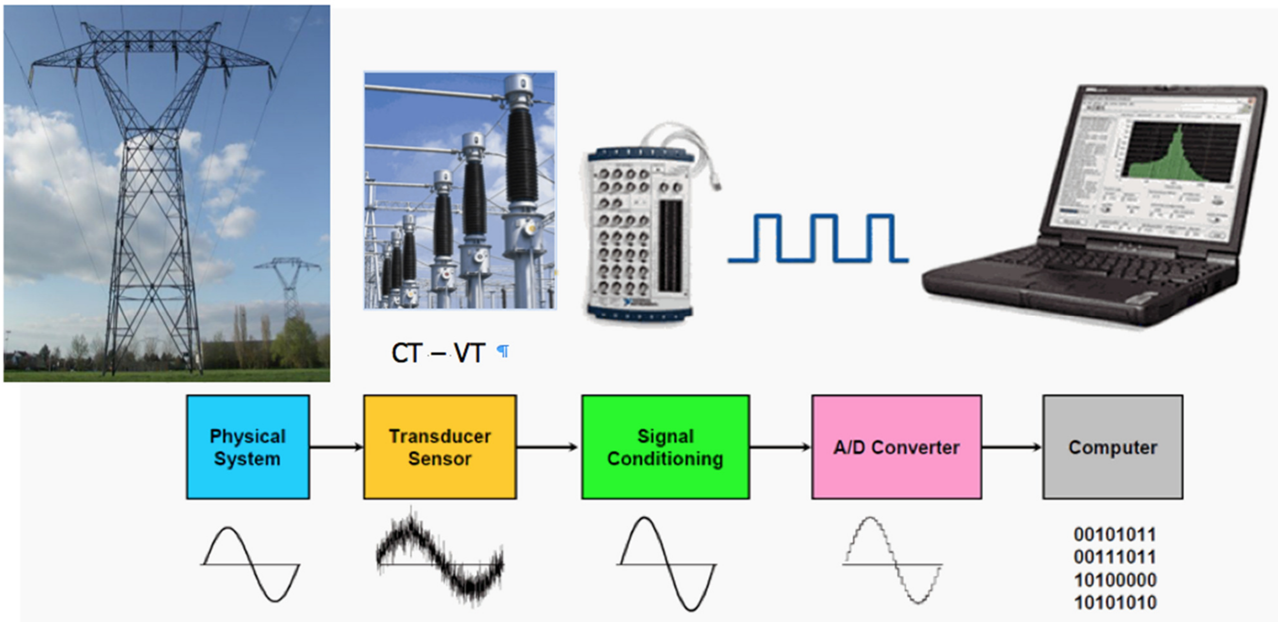


Figure 18: Data acquisition process.

The transducers are the measurement transformers that convert the electrical MV or HV signals (voltage and current) into a corresponding smaller signal which will be handled by the acquisition system. This acquisition system depends on the characteristics of the secondary signals of the measurements transformers. For example, the secondary current given by the CT will be converted into a voltage signal that will be easily handled by the A/D converter. Signal conditioning may be necessary if the signal from the transducer is not suitable for the DAQ hardware being used. The signal may need to be filtered or amplified in most cases. The DAQ hardware is what usually interfaces between the signal and a PC.

4.3.2 A/D converter

The analog-to-digital converter or A/D converter is the device that converts a continuous physical quantity (usually a voltage) to a digital number that represents the quantity's amplitude (voltage and current).

The conversion involves quantization of the input, so it necessarily introduces a (small) amount of error. Instead of doing a single conversion, an AD converter often performs the conversions periodically by "sampling" the input. The result is a sequence of digital values that have been converted from a continuous-time and continuous-amplitude analog signal to a discrete-time and discrete-amplitude digital signal.

The AD converter is defined by its bandwidth (the range of frequencies it can measure) and its signal to noise ratio (how accurately it can measure a signal relative to the noise it introduces). The actual bandwidth of an AD converter is characterized primarily by its sampling rate, and to a lesser extent by how it handles errors such as aliasing. The dynamic range of an AD converter is influenced by many factors, including the resolution (the number of output levels it can quantize a signal to), linearity and accuracy (how well the quantization levels match the true analog signal) and jitter (small timing errors due to the use of a non-ideal sampling clock that introduce additional noise). The dynamic range of an AD converter is often summarized in terms of its effective number of bits (ENOB), the number of bits of each measure it returns that are on average not noise. An ideal AD converter has an ENOB equal to its resolution. AD converters are chosen to match the bandwidth and required signal to noise ratio of the signal to be quantized. If an AD converter operates at a sampling rate greater than twice the bandwidth of the signal, then perfect reconstruction is possible given an ideal AD converter and neglecting quantization error. The presence of quantization error limits the dynamic range of even an ideal AD converter. However, if the dynamic range of the AD converter exceeds that of the input signal, its effects may be neglected resulting in an essentially perfect digital representation of the input signal.

4.3.3 Resolution

The resolution of the converter indicates the number of discrete values it can produce over the range of analog values. The resolution determines the magnitude of the quantization error and therefore determines the maximum possible average signal to noise ratio for an ideal ADC without the use of oversampling. The values are usually stored electronically in binary form, so the resolution is usually expressed in bits. In consequence, the number of discrete values available, or "levels", is assumed to be a power of two. For example, an AD converter with a resolution of 8 bits can encode an analog input to one in 256 different levels, since $2^8 = 256$. The values can represent the ranges from 0 to 255 (i.e. unsigned integer) or from -128 to 127 (i.e. signed integer), depending on the application.

Resolution can also be defined electrically, and expressed in volts. The minimum change in voltage required to guarantee a change in the output code level is called the least significant bit (LSB) voltage. The resolution Q of the AD converter is equal to the LSB voltage. The voltage resolution of an AD converter is equal to its overall voltage measurement range divided by the number of discrete values:

$$Q = \frac{E_{FSR}}{2^M} = \frac{V_{inputHigh} - V_{inputLow}}{2^M} \qquad (17)$$

where:

E_{FSR} is the full scale voltage range (also called 'span') given by the difference between $V_{inputHigh}$ and $V_{inputLow}$, the upper and lower extreme values of the input voltage;

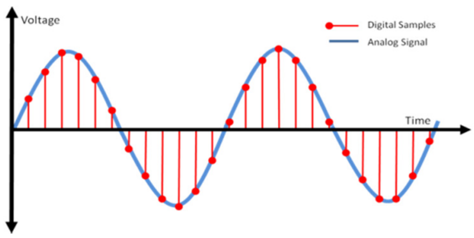
M is the AD converter's resolution in bits.

Normally, the number of voltage intervals is given by:

$$N = 2^M \qquad (18)$$

That is, one voltage interval is assigned in between two consecutive code levels.

These concepts are illustrated by Figure 19 and the following example.



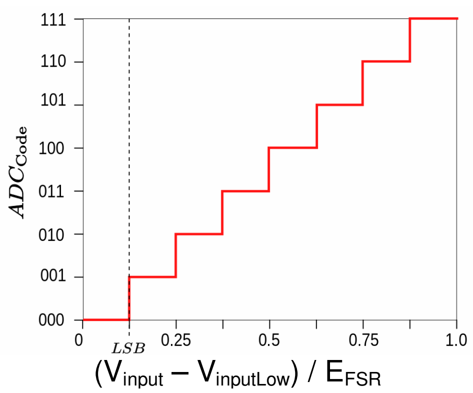


Figure 19: Conversion of an analog signal into a digital signal and coding scheme.

Example:

- Coding scheme as in Figure 19 assuming an input signal x(t) = A cos(t), A = 5 V;
- Full scale measurement range = -5 to 5 volts;
- ADC resolution is 8 bits: 2^8 = 256 quantization levels (codes);
- ADC voltage resolution, Q = (5 V – (–5 V)) / 256 = 10 V / 256 ≈ 0.039 V ≈ 39 mV.

The errors are measured in a unit called the least significant bit (LSB). In the above example of an 8-bit AD converter, an error of one LSB is 1/256 of the full signal range, or about 0.4%.

In practice, the useful resolution of a converter is limited by the best signal-to-noise ratio (SNR) that can be achieved for a digitized signal. The SNR is a measure that compares the level of a desired signal (meaningful information) to the level of background noise (unwanted signal). It is defined as the ratio of signal power to the noise power, often expressed in decibels. A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise.

An AD converter can resolve a signal to only a certain number of bits of resolution, called the effective number of bits (ENOB). One effective bit of resolution changes the signal-to-noise ratio of the digitized signal by 6 dB, if the resolution is limited by the AD converter. If a preamplifier has been used prior to A/D conversion, the noise introduced by the amplifier can be an important contributing factor towards the overall SNR.

4.3.4 Quantization error

Quantization is the process of mapping a large set of input values to a (countable) smaller set – such as rounding values to some unit of precision.

In analog-to-digital conversion, the difference between the actual analog input voltage and the quantized digital value is called quantization error or quantization distortion. This error is either due to rounding or truncation. The error signal is sometimes modeled as an additional random signal called quantization noise because of its stochastic behaviour. The noise is non-linear and signal-dependent. The Figure 20 depicts the original signal, the digitized signal and the quantization error, with reference to the example dealt with in Figure 19.

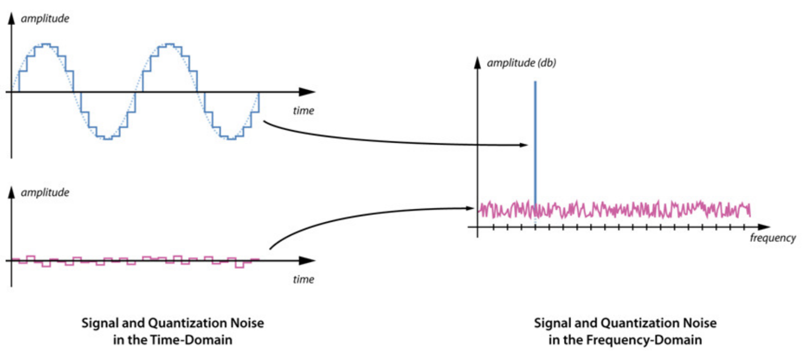


Figure 20: Signal and quantization noise.

4.3.5 Sampling rate

The analog signal is continuous in time and it is necessary to convert this to a flow of digital values. It is therefore required to define the rate at which new digital values are sampled from the analog signal. The rate of new values is called the sampling rate or sampling frequency of the converter.

A continuously varying band limited signal can be sampled (that is, the signal values at intervals of time T_s, the sampling time, are measured and stored) and then the original signal can be reproduced from the discrete-time values by an interpolation formula. The accuracy is limited by quantization error. However, a faithful reproduction is possible if (and only if) the sampling rate is higher than twice the highest frequency of the signal. This is essentially what is embodied in the Shannon-Nyquist sampling theorem.

If the voltage input function x(t) contains no frequencies higher than f_{max} Hz, it is completely determined by giving its ordinates at a series of points spaced $1/(2f_{max})$ seconds apart. A sufficient sample-rate is therefore 2 f_{max} samples/second, or anything larger. Equivalently, for a given sample rate f_s, perfect reconstruction is guaranteed possible for a bandlimit $f_{max} \leq f_s/2$.

$$f_s \geq 2 f_{max} \quad (19)$$

When the bandlimit is too high (or there is no bandlimit), the reconstruction exhibits imperfections known as aliasing. To avoid aliasing, the input to an AD converter must be low-pass filtered to remove frequencies above half the sampling rate.

4.4 Synchronized measurements

4.4.1 General

The use of time synchronizing techniques, coupled with the computer-based measurement technique, to measure phasors and phase angle differences in real time is required to allow the comparison of current and voltage signals measured at different points of the network in the same time base.

Phasor Measurement Units (PMU) shall be used to provide a common time source for synchronization. The PMUs are power system devices that provide synchronized measurements of real-time phasors of voltages and currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) Satellite. Time synchronization allows synchronized real-time measurements from multiple remote measurement points on the grid.

A phasor is a complex number that represents both the magnitude and phase angle of the sine waves like the currents and the voltages. Phasor measurements that occur at the same time are called "synchrophasors". Phasor measurements are sampled from widely dispersed locations in the power system network and synchronized from the common time source of a Global Positioning System (GPS) radio clock. The synchrophasors provide a useful tool for system operators to measure the state of the electrical system and manage the power quality.

PMUs measure voltages and currents at critical points on the power grid and they output accurately time-stamped voltage and current phasors. Because these phasors are truly synchronized, synchronized comparison of two quantities is possible in real time. These comparisons can be used to assess system conditions such as frequency and voltage changes.

The phasor data is collected either on-site or at centralized locations using Phasor Data Concentrator technologies and Supervisory Control and Data Acquisition (SCADA) systems. The data is then transmitted to a monitoring system allowing the control of the power flows on the network.

The standard for synchrophasors is the IEEE C37.118-2005 which was completed in 2005. The specification describes standards for measurement, the method of quantifying the measurements, testing and certification requirements for verifying accuracy, and data transmission format and protocol for real-time data communication. A new version of the standard was released in December 2011, which split the IEEE C37.118-2005 standard into two parts: C37.118-1 dealing with the phasor estimation and C37.118-2 the communications protocol. It also introduced two classifications of PMU, M for measurement and P for protection. M class is close in performance requirements to that in the original 2005 standard, primarily for steady state measurement. P class has relaxed some performance requirements and is intended to capture dynamic system behaviour.

The requirements for IT infrastructure to guarantee 'real time' data exchange are out of scope in this document but it is worth to mention the application of IEC 61850 protocol that is of great interest in electrical power systems for data communication systems between substations. This IEC 61850 protocol offers new possibilities for real-time communication performance between Intelligent Electronic Devices (IEDs) within substation and between substations and the observation and monitoring center because of the Generic Object Oriented Substation Event (GOOSE) messages.

4.4.2 Fundamentals of PMUs

PMUs technology provides phasor information, both magnitude and phase angle, in real time. The advantage of referring phase angle to a global reference time is helpful in capturing the wide area snapshot of the power system.

A pure sinusoidal waveform can be represented by a unique complex number known as a phasor. Consider a sinusoidal signal, voltage or current:

$$x(t) = X_m \cos(\omega t + \varphi) \quad (20)$$

The phasor representation of this sinusoid is given by:

$$\underline{X} = X\ e^{j\varphi} = \frac{X_m}{\sqrt{2}} (\cos\varphi + j\sin\varphi) \quad (21)$$

where:

$X = X_m/\sqrt{2}$ is the magnitude of the phasor, the rms value of the sinusoidal signal;

φ is the phase angle.

The signal frequency ω is not explicitly stated in the phasor representation.

The sinusoidal signal and its phasor representation are illustrated in Figure 21.

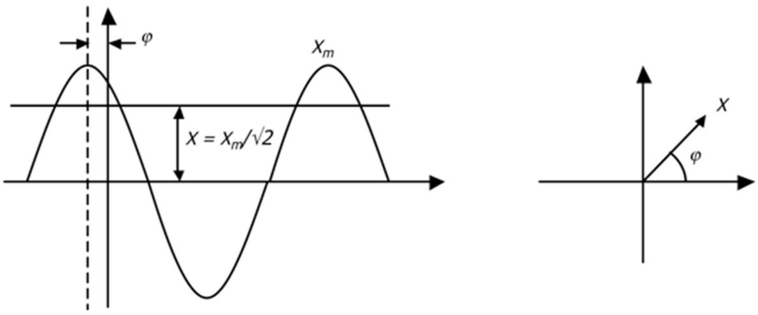


Figure 21: Sinusoidal signal and its phasor representation.

Positive phase angles are measured in a counterclockwise direction from the real axis. Since the frequency of the sinusoid is implicit in the phasor definition, it is clear that all phasors which are included in a single phasor diagram must have the same frequency. Phasor representation of the sinusoid implies that the signal remains stationary at all times, leading to a constant phasor representation. These concepts must be modified when practical phasor measurements are to be carried out when the input signals are not constant in frequency.

Although a constant phasor implies a stationary sinusoidal waveform, in practice it is necessary to deal with phasor measurements which consider the input signal over a finite data window. In many PMUs the data window in use is one period of the fundamental frequency of the input signal. If the power system frequency is not equal to its nominal value (it is seldom), the PMU uses a frequency-tracking step and thus estimates the period of the fundamental frequency component before the phasor is estimated. It is clear that the input signal may have harmonic or non harmonic components. The Task of the PMU is to separate the fundamental frequency component and find its phasor representation.

The most common technique for determining the phasor representation of an input signal is to use data samples taken from the waveform, and apply the Discrete Fourier Transform (DFT) to compute the phasor. Since sampled data are used to represent the input signal, it is essential that antialiasing filters (see paragraph 4.3.5) be applied to the signal before data samples are taken. The antialiasing filters are analog devices which limit the bandwidth of the pass band to less than half the data sampling frequency satisfying the Nyquist criterion.

If x_k, { k = 0, 1, 2, 3, …, N-1 } are the N samples of the input signal taken over one period, then the phasor representation is given by the fundamental frequency of the Discrete Fourier Transform (DFT):

$$X = \frac{\sqrt{2}}{N} \sum_{k=0}^{N-1} x_k e^{-j\frac{2\pi}{N}k} \qquad (22)$$

The DFT calculation eliminates the harmonics of the input signal. However, the non-harmonic signals and any other random noise present in the input signal leads to an error in estimation of the phasor.

The Discrete Fourier Transform is a simple and widely used method for phasor estimation but other methods can be suggested like Kalman filters, weighted least squares or neural networks.

As explained above, synchrophasor is a term used to describe a phasor which has been estimated at an instant known as the time tag of the synchrophasor. In order to obtain simultaneous measurement of phasors across a wide area of the power system, it is necessary to synchronize these time tags, so that all phasor measurements belonging to the same time tag are truly simultaneous.

Consider the marker t = 0 in Figure 21 is the time tag of the measurement. The PMU must then provide the phasor given by (21) using the sampled data of the input signal (22). Note that there are antialiasing filters present in the input of the PMU, which produce a phase delay depending upon the filter characteristic. Furthermore, this delay will be a function of the signal frequency. The Task of the PMU is to compensate for this delay because the sampled data are taken after the antialiasing delay is introduced by the filter. This is illustrated in Figure 22. The synchronization is achieved by using a sampling clock which is phase locked to the one pulse per second signal provided by a GPS receiver. The receiver may be built in the PMU, or may be installed in the substation and the synchronizing pulse distributed to the PMU and to any other device which requires it. The time tags are at intervals that are multiples of a period of the nominal power system frequency.

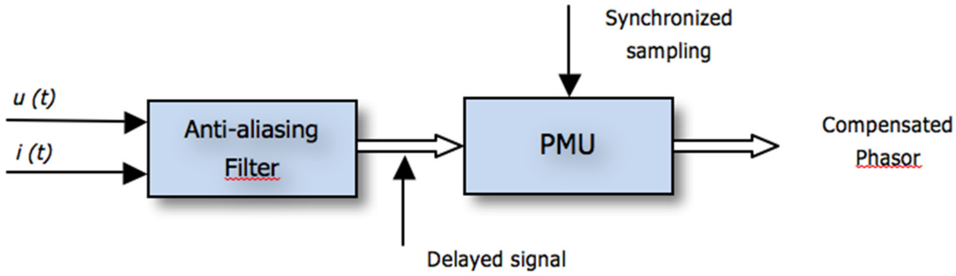


Figure 22: Anti-aliasing filter and compensation of the signal delay.

4.4.3 General block diagram of a PMU

The civilian-use channel of the GPS system transmits positional coordinates of the satellites from which the location of a receiver station on earth could be determined. In addition, the satellites transmit a one pulse per second signal, along with an identifier for the signal that can be interpreted by the earth station receivers. The civilian-use transmission of the time signal is precise to within 1 microsecond, and often in practice is found to be much more accurate. The time pulse is of critical importance to the application considered here. The normal practice is to phase lock a sampling clock to this pulse. The sampling instant would be identified as the pulse number within a one second interval identified by the GPS time-tag. The exact format for time-tagging is defined in IEEE standard C37.118-2005. It should be mentioned that a time standard known as the IRIG-B standard is currently being used by the power industry for time-tagging digital fault recorders and other substation event monitoring systems. However, with standard IRIG-B receivers the synchronization accuracy is of the order of 1 millisecond, which is not enough for precise power system measurement (a tolerance of 1 millisecond corresponds to an uncertainty of about 20°).The complete block diagram of a PMU and its integration in a power system are shown in Figure 23 and Figure 24.

The PMU can measure the 50 Hz ac waveforms (voltages and currents) at high rate up to 160 samples per cycle (8 kHz or 8000 samples per second for 50 Hz systems). The analog ac waveforms are digitized by an analog to digital converter for each phase. A phase-lock oscillator along with a GPS reference source provides the needed high speed synchronized sampling with 1 microsecond accuracy. The phasors are then computed using DFT-like algorithms. Then, the resultant time tagged phasors can be transmitted to a local or remote receiver at rates up to 60 samples per second.

Depending on the characteristics and PMU accuracy, the total vector error is about 1%, 0.2% magnitude resolution and 0.3 degree phase resolution. The frequency is measured with an accuracy of 1 mHz.

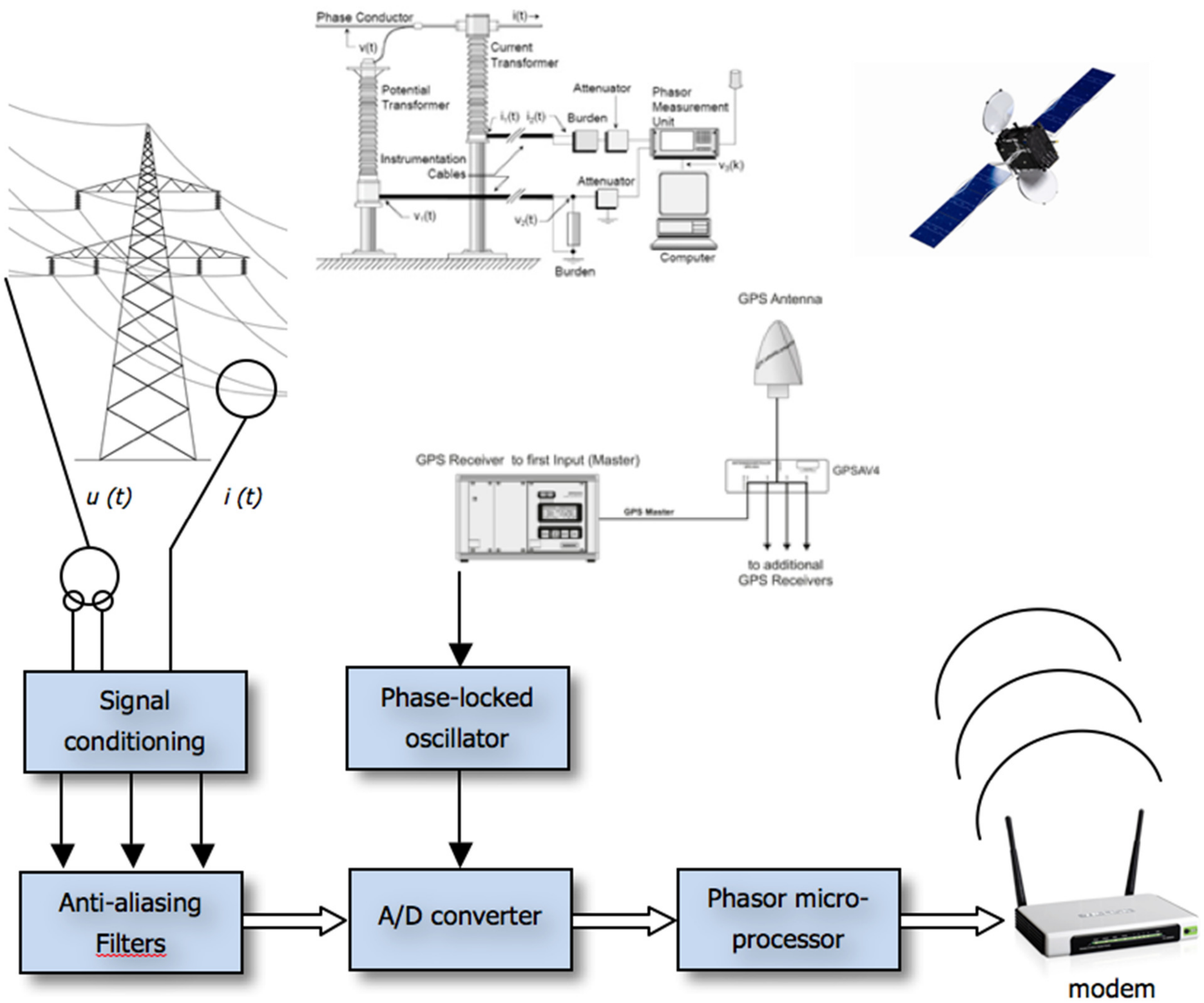


Figure 23: General block diagram of a PMU.

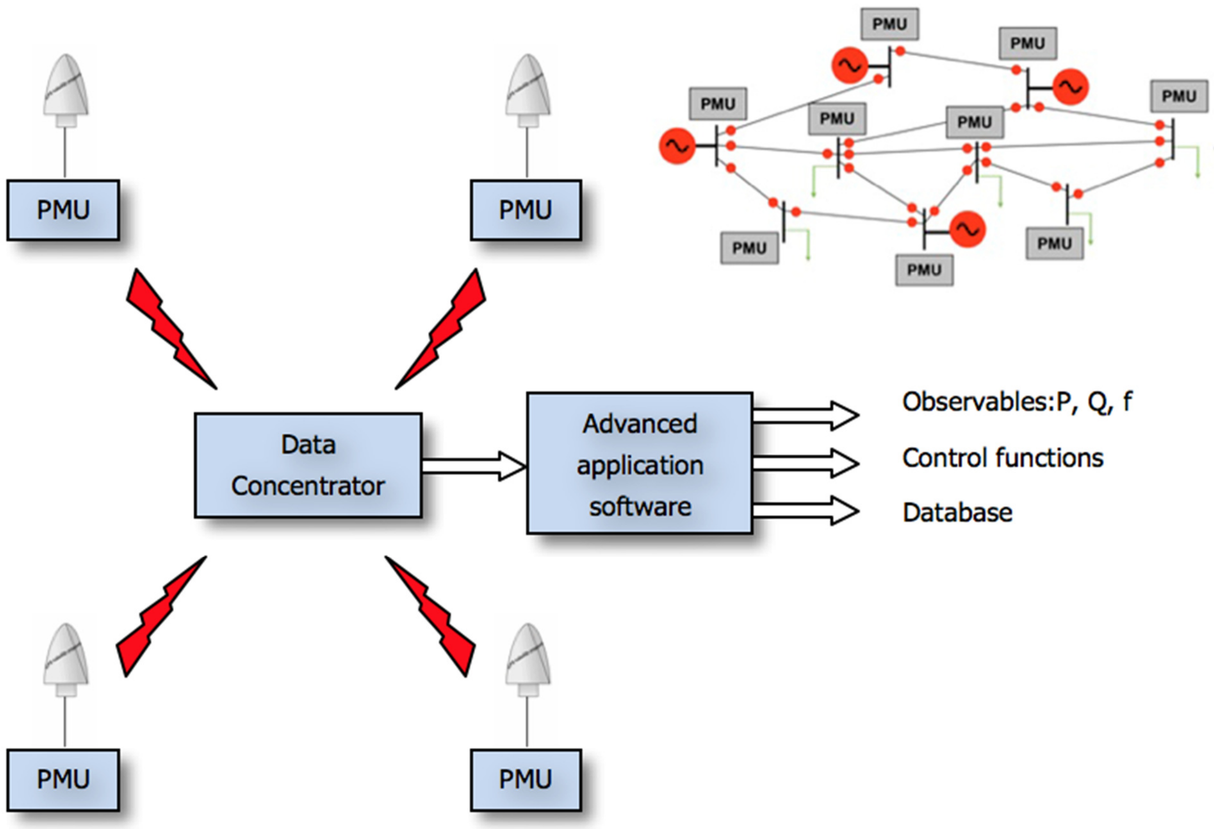


Figure 24: Integration of PMUs in the power system.

4.4.4 Discrete Fourier Transform

The discrete Fourier transform can be considered as the generalisation of the continuous Fourier transform to the case of a discrete function known only at instants separated by sample times T_s (i.e. a finite sequence of data).

Let x(t) be the continuous signal which is the source of the data. Let N samples be denoted $x_k = x(t_k)$, { k = 0, 1, 2, 3, …, N-1 , $t_k = k\,T_s$ }, the signal at N instants separated by sample time T_s.

The Fourier transform of the original continuous-time signal x(t) is:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)\, e^{-j\,\omega t}\, dt \qquad (23)$$

Since the discrete signal $x(t_k)$ only exists at the sample points, the DFT replaces the infinite integral with a finite sum:

$$X(\omega_n) = \sum_{k=0}^{N-1} x(t_k)\, e^{-j\,\omega_n t_k} \qquad n = 0, 1, 2, \dots N-1 \qquad (24)$$

Since the operation treats the data as if it were periodic, the DFT equation is evaluated for the fundamental frequency (one cycle per sequence) and its harmonics (not forgetting the dc or average component ω = 0):

$$\omega = 0, \quad \frac{2\pi}{NT_s}, \quad \frac{2\pi}{NT_s} \cdot 2, \quad \frac{2\pi}{NT_s} \cdot k, \ldots, \quad \frac{2\pi}{NT_s} \cdot (N-1) \qquad (25)$$

or

$$\omega_n = \frac{2\pi}{NT_s} n \qquad n = 0, 1, 2, \ldots N-1 \qquad (26)$$

The DFT equation (24) is then rewritten:

$$X_n = \sum_{k=0}^{N-1} x_k \, e^{-j\frac{2\pi}{N}n\,k} \qquad n = 0, 1, 2, \ldots N-1 \qquad (27)$$

And the inverse transform is:

$$x_k = \frac{1}{N} \sum_{n=0}^{N-1} X_n \, e^{j\frac{2\pi}{N}n\,k} \qquad k = 0, 1, 2, \ldots N-1 \qquad (28)$$

The discrete Fourier transform (DFT) converts a finite list of equally spaced samples x_k of a function x(t) into the list of coefficients X_n of a finite combination of complex sinusoids, ordered by their frequencies, that has those same sample values. It can be said to convert the sampled function from its original time domain to the frequency domain.

Discrete Fourier transforms (DFTs) are extremely useful because they reveal periodicities in input data as well as the relative strengths of any periodic component. There are however a few subtleties in the interpretation of discrete Fourier transforms. In general, the discrete Fourier transform of a real sequence of numbers will be a sequence of complex numbers of the same length. In particular, if x_k are real, then X_n and X_{N-n} are complex conjugate (the component X_0 is always real for real data). As a result of the above relation, a periodic function will contain transformed peaks in not one, but two places. This happens because the periods of the input data become split into "positive" and "negative" frequency complex components. The spectrum X_n is symmetrical about N/2.

4.4.5 Frequency estimation

The frequency estimation is described in the section “Determination methods for specific observables”. We only mention here the methods which are found in the literature:

- Zero crossing;
- Least error squares;
- Kalman filters;
- Demodulation;
- Phasor measurement angle changing.

For our purposes, the frequency should be measured with an accuracy of 1 mHz.

5 Future Measurements Methods

The principles presented in the next paragraphs describe the next generation of measurements methods. Some new sensors have already reached an industrial maturity level while others are still in a research stage. These principles are studied for High Voltage measurements.

These new methods will eventually replace the conventional ones because they will show better performances. They should also be cheaper.

5.1 Optical sensors

These sensors use the influence of an electric or magnetic field on particular materials optical properties to measure either current or voltage through the use of light beams.

This kind of sensors promises better accuracy, security and compactness. Further, they will have a much better immunity to electromagnetic perturbations and will have a bigger range of frequency (up to several kHz).

Several devices have already been implemented in the USA since 1999 and the feedback of the exploitation is very good. However, although the technology is nearing industrial maturity, a large-scale exploitation isn't for today, since there is a lot to be done regarding the communication channel interoperability with the existing systems.

5.1.1 Optical current sensor

This sensor uses the Faraday effect to measure the current in a conductor. The Faraday effect describes the way a magnetic field applied on a transparent material (like glass) alters its optical properties and changes the polarity of a light beam going through it.

The principle, whose schematic can be seen in Figure 25, is the following:

- A LED emits a light beam which is parallel to the magnetic field of the current we want to measure. This light beam has a certain polarity which is known.
- The beam goes through a block of glass, whose optical properties are altered by the electromagnetic field. The result is that the polarity of the light beam (which is in fact an electromagnetic wave) is modified by the application of the magnetic field.
- The beam goes then through a polarizer which will convert the change in polarity in change of intensity.
- Finally, a photodiode receives the beam and translates the light signal in a analog electric signal.

The current can thus be measured through the intermediary of the magnetic field. The accuracy is very good since the error is lower than 0,1%. The bandwidth ranges between 0 and 5 kHz.

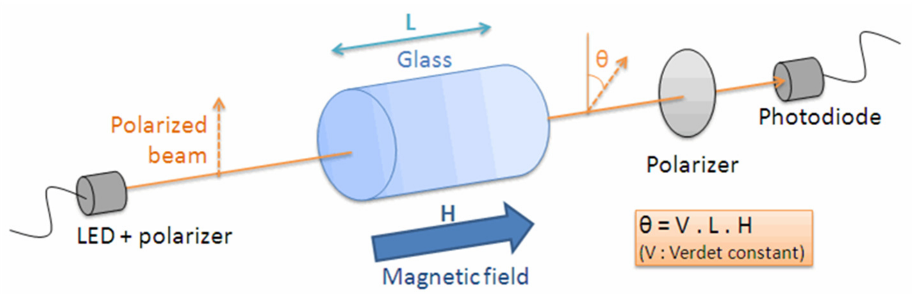


Figure 25: Principle of the optical current sensor.

Figure 26 and Figure 27 illustrate two examples of sensors.

Figure 26: Example of an optical current sensor (in the foreground) and a conventional current transformer (in the background) for medium and high voltage applications (1 kV-50 kV).

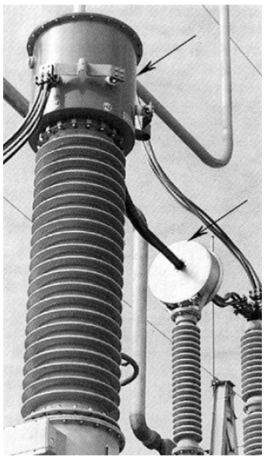


Figure 27: Example of an optical current sensor (in the background) and a conventional current transformer (in the foreground) for high voltage applications (> 50 kV).

5.1.2 Optical voltage sensor

This sensor uses the Pockels effect to measure the voltage between two conductors. The Pockels effect describes the way an electric field applied on a certain type of crystal alters its optic properties and changes the polarity of a light beam going through it.

The principle, whose schematic can be seen in Figure 28, is very similar to the one of the optical current sensor, except that the light beam is this time parallel to the electric field created between the two conductors by the voltage difference, and that its polarization is altered by the electric field and not the magnetic field.

The voltage can thus be measured through the intermediary of his electric field.

This technology is less mature than the correspondent current sensor, so there isn't yet a real REX at the moment.

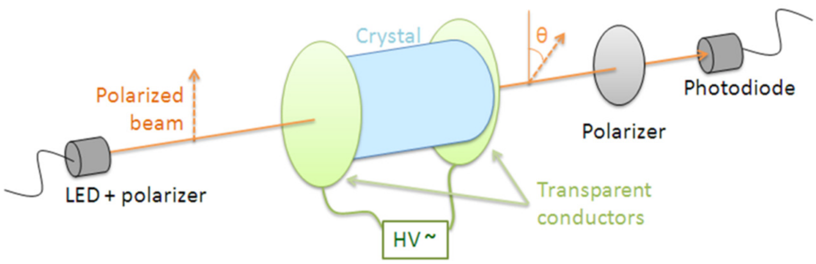


Figure 28: principle of the optical voltage sensor.

Figure 29 shows a prototype developed for the US Navy by PPi.

Figure 29: Prototype of a optical (high) voltage sensor developed by PPi.

5.2 Rogowski coil current sensor

This sensor has the same working principle as a current transformer, but it has no ferromagnetic core, and consequently no magnetic circuit. Besides, The ratio between the load resistance and the intern resistance is much higher than in typical current transformers.

The absence of a magnetic circuit allows a perfect linearity in a wide range of current. This is why one of the field of usage of this device is the measurement of harmonic current content.

One of the advantages of the Rogowski sensor is that due to its low inductance, it can respond to fast-changing currents, thus measuring higher frequencies. It is also supposed to be a lot cheaper than conventional current transformers.

Although its principle has been described in 1912, this sensor has been developed for High Voltage Networks only since 1986 and isn't widespread yet. Its applications are potentially unlimited, since it can measure currents from less than 100 mA to more than 300 kA, and detect frequencies between 0.1 Hz and 30 MHz [14]. Their accuracy is typically ±0.2%.

An illustration of its working principle in shown in Figure 30.

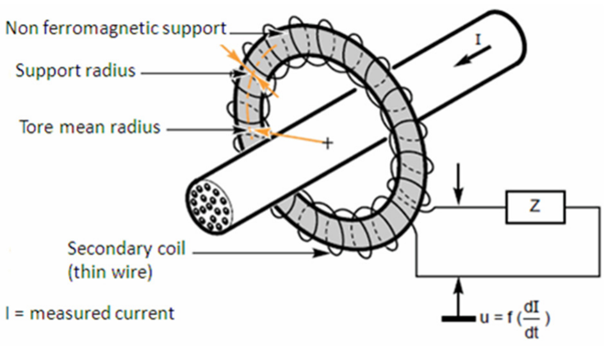


Figure 30: Principle of the Rogowski coil current sensor.

Figure 31 presents an example of a product available on the market.

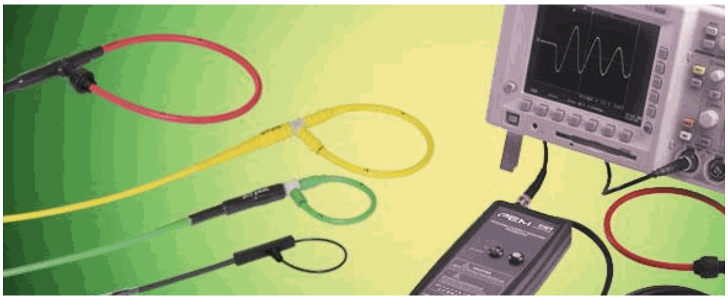


Figure 31: Rogowski coil current sensors from PEM [14].

5.3 Hall effect current sensor

Initially used to measure a magnetic field, the Hall effect sensor can also be used to measure indirectly currents, since any current produces a certain magnetic field. The Hall effect current sensor can also measure DC currents.

The principle of a Hall effect sensor, whose schematic can be seen in Figure 32, is the following:

- A magnetic circuit is set around the conductor in which the current we want to measure is flowing in order to concentrate the magnetic field. There is a small air gap in the magnetic circuit.
- A semiconductor probe is set in the air gap and an auxiliary current is flowing in the probe, perpendicularly to the magnetic field in the air gap.
- The Hall effect predicts that if a current is flowing perpendicularly to a magnetic field, a voltage difference will appear between both exterior faces of the probe, in a direction which is perpendicular both to the magnetic field and to the current flow.
- The measure is then operated on this voltage difference.

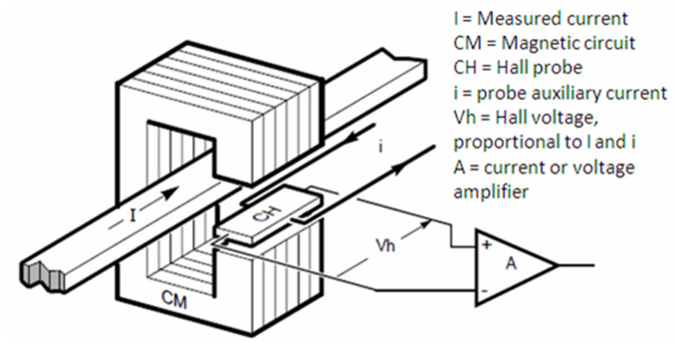


Figure 32: Princi effect sensor.

The measure might unfortunately suffer from three different error sources:

- an offset voltage, due to the conception of the probe;
- a non-linearity, due to the presence of a magnetic circuit;
- a fluctuation due to the temperature change (K typically varies 0,01%/°C).

Figure 33 illustrates two examples of Hall effect current sensor.

Figure 33: examples of Hall effect current sensors

5.4 Zero flux current sensor

This sensor is able to measure DC currents and has a very good accuracy. Unfortunately, because of its working principle, it requires a very protected electromagnetic environment.

The working principle, whose schematic can be seen in Figure 34, is the following:

- A magnetic circuit is set around the conductor in which the measured current I_1 is flowing.
- A coil is put around the magnetic circuit. A current I_2 flows in the coil, in order to cancel the flux produced by the current I_1 in the magnetic circuit.
- The magnitude of the current I_2 is regulated by an electronic amplifier which is controlled by the voltage amplitude at the extremities of a second coil around the magnetic circuit. This voltage will be produced by the flux in the circuit.
- This regulation cancels the flux in the magnetic circuit and allows to measure the current I_1 by means of the current I_2.

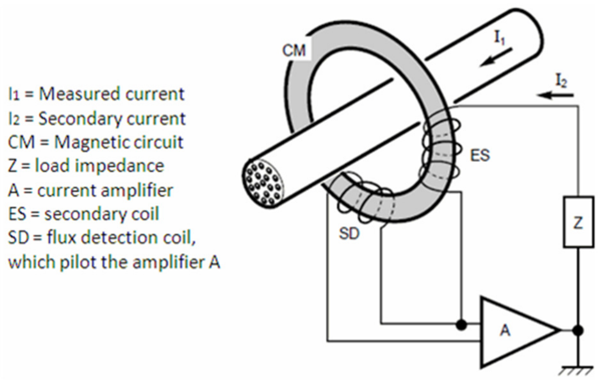


Figure 34: Principle of the Zero flux current sensor.

Devices currently on the market can converts currents up to 200 A with a linearity error of 1 ppm and can work from DC up to frequencies of 100 kHz with a flat frequency response.

Two examples of a Zero flux current sensor can be seen in Figure 35 for illustration.

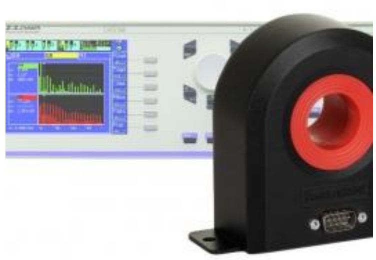


Figure 35: examples of zero flux current sensors.

5.5 Medium voltage capacitive dividers (VCD)

Capacitive dividers used in medium voltage are very similar in their principle to the capacitive voltage transformer shown in paragraph 3.4. The difference is that in medium voltage applications they are used only to notify the presence of the voltage and not to measure it. The presence of the voltage is shown by a LED which is lighted by the mentioned voltage. Thus a maintenance team that have to work on the lines can be warned if there remains a residual voltage. The idea is to use that widespread device in medium voltage substations to measure active and reactive power flows via the voltage measurement.

The problem is that the power delivery capability of this type of capacitive dividers is very limited. Furthermore, connecting standard equipment to the VCD would introduce a change of ratio and phase and the measurement would become frequency dependent. An interface between the standard PQ measurement equipment and the VCD is thus necessary, especially to amplify the signal. Voltage conditioning boxes are available on the market. They have been tested in medium voltage substations for distribution networks to assess the feasibility of this type of measurement. The results showed that the voltage conditioner performs very well and that high accuracy was found for waveforms, harmonics ($\varepsilon \approx 0.5\%$ up to harmonic 11), RMS values ($\varepsilon \approx 1\%$), ripple control signals ($\varepsilon \approx 0.01\%$) and the phase shift ($\Delta\varphi \leq 0.2°$).

5.6 Standards

IEEE Standard C37.118-2005, IEEE Standard for Synchrophasors for Power Systems.

IEC 61000-4-30, Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques - Power quality measurement methods.

IEC 61000-4-7, Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.

6 References

[1] IEEE Standard C37.118-2005, IEEE Standard for Synchrophasors for Power Systems.

[2] IEC 61000-4-30, Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques - Power quality measurement methods.

[3] IEC 61000-4-7, Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.

[4] IEC 61689-1, General requirements for instrument transformers.

[5] IEC 61689-2, Additional requirements for current transformers.

[6] IEC 61689-3, Additional requirements for inductive voltage transformers.

[7] IEC 61689-5, Additional requirements for capacitive voltage transformers.

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