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WP 6

Control schemes for the use of Flexibility

Deliverable 6.1

Functional specification of the control functions for the control of flexibility across the different control boundaries

20/12/2015

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This Intermediate Version of this D6.1 document outlines a methodology specifically created for developing and testing Control Functions for the Web-of-Cells (WoC) concept and their functional specifications.

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Executive summary

This intermediate Version of this D6.1 document outlines a methodology specifically created for developing and testing Control Algorithms for the newly coined Web-of-Cells (WoC) concept. One of the most important lessons learned in this task is that development of such a radical new concept as WoC for control of the future power system with a high share of Renewable Energy Sources (RES) is a challenging process. It requires rethinking of several well-established fundamental principles in the power system domain. Instead of conventional voltage and frequency controls, Balance and Voltage types of control have been introduced. These require introduction of several new terms of definitions, which have been proposed in cooperation with ELECTRA Work Package 5. 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).

This intermediate deliverable describes objectives, control functions and identified number of control triples for the Main Use Cases. These Control Triples originate from deliverable D5.2, and provided the basis for the intended operation of the Control Functions.

The implementation and selection of control functions for main Use Cases are explained where the control is divided into “Supervisory control” and “Service control”. The document describes also the time sequence representations among different actors for intra and inter-cell control. The time sequence diagrams of use cases include also the functional specifications of control functions.

By applying the developed methodology, a selection of not commonly used Control Functions has been made that serves the main Use Cases defined in ELECTRA Deliverable D3.1 "*Specification of Smart Grids high level functional architecture for frequency and voltage control*". A preference list of Use Cases is suggested to be developed further and to be tested in the lab

The results so far also indicate that the WoC concept together with the above mentioned methodology, built on top of the well-known Use Case methodology, allow for determining Control Functions for an electric power system supporting future energy systems in a tractable manner.

Terminologies

Definitions

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

Additionally the Deliverable D5.2 document introduces several new terms and definitions, which have been specifically developed in WP5 "Increased Observability" for the scope of the ELECTRA project, or have a meaning which may differ from the commonly used meaning.

The text below shows a selection of the key definitions, in accordance with the similar list in Deliverable 5.2, "Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes".

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

Term	Definition
	(For more detailed definition of the Control Topology Levels see the chapter 21.5. "Working procedure for selecting control functions for Use Cases")
Balance Control	Control loops that serve to keep the power balance between generation and loads, irrespective of the observable used for balance monitoring.
Voltage Control	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, 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

ADMM	Alternating direction method of multipliers
BRC	Balance Restoration Control
CTL	Control Topology Levels
CTS	Control Time Scales
FCC	Frequency Containment Control
HLUC	High Level Use Case
IRPC	Inertia Response Power Control
NPFC	Network Power Frequency Characteristic
RES	Renewable Energy Sources
SGAM	Smart Grid Architecture Model
SRPS	Single Reference Power System
UC	Use Case
VPP	Virtual power plants

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1 Introduction to control schemes for the use of flexibility

The purpose of the ELECTRA project is to research radical control solutions for the real time operation of the 2030 power system. The control solutions utilise the flexibility from across traditional boundaries (of voltage level, stakeholders, license areas, etc.) in a holistic fashion to build ubiquitous sensing with dynamic and autonomous control functions under normal and disturbed conditions.

The main objective of work package 6 (WP6) “Control schemes for the use of Flexibility” within the ELECTRA project is to design and develop control functions. The focus is frequency and voltage control at the transmission level, but control objectives and contributions from the distribution level, will be fully considered.
A number of national and European projects have demonstrated the utilisation of flexibility within individual categories of grid connected devices, such as various types of domestic load, electric vehicles (EV) charging, storage, and virtual power plants (VPPs) with distributed generation. This work package builds on this body of work but importantly addresses the problem holistically. The work will consider the flexibility of different types of resources (demand, generation, storage, interconnection, network automation, and network devices) and the coordinated utilisation of dispatchable resources taking account of the inherent fast-acting response of other devices. The solutions exploit the flexibility in control and protection schemes in order to adapt to changing power system states. Such schemes must take account of inherent dynamic response, local controls, centralised control actions, decentralised controls, and direct and price driven control mechanisms. This work will include the flexible provision for both voltage and frequency control.

Effective control and equitable distribution of rewards requires the flexibility resources to be measurable/metered. Control actions must take into account the confidence bands associated with these observations. Such flexibility must be able to be exercised under emergency and restorative conditions as well as normal operating conditions. The solutions are compatible with the Smart Grid Architecture Model (SGAM), and they use the flexibility available at smart grid connection points and in the network provided by a diverse group of actors – individual prosumers, large generators, network operators, aggregators, and suppliers. The work is also aligned with the high profile of flexibility in Strategic Research Agenda (SRA2035), especially research area IS “Integrated truly sustainable, secure and economic electricity Systems”. This work package will develop key elements that contribute to the realisation of the new system control architectures. The work has close link to development within the European Energy Research AAllicance, Joint Program Smart Grid, Sub-program 1: Network operation (= EERA JP SG SP1). Likewise the control techniques will incorporate the flexibility available from storage resources in EERA SG JP Sub-program 4: Electrical storage integration and interoperability issues available in Sub-program 3: Information and control systems interoperability.

This intermediate deliverable describes the work of ELECTRA Task 6.2 “Development of robust coordination functions for multiple controllers across different control boundaries”. T6.2 includes two phases:

- Phase 1 is the conceptual phase where the detailed concepts of the control solution are worked out and described, starting from the proposed overall solution named the “Web-of-Cells” concept and six high level Use Cases which were developed in WP3 and WP4 and is described in deliverable D3.1 of WP3.

- Phase 2 will follow the project-wide milestone 2 (M20) and T6.2 will continue with the design and development of the various control functions based on the detailed system specifications provided by WP4. The design, development, and module testing of the control functions will be done in T6.2. These are the software modules that will be used for integration and overall solution lab-testing in WP7.

Radical control solutions will be researched and developed for the real time operation of the 2030 power system. The effort of Task 6.2 will reveal techniques that take us beyond the foreseeable smart grid, and will give significant insight into the types of solutions required for real time operation of the power system in 2030. The work of T6.2 has been divided into the following Sub-Tasks:

1. Development of autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives.
2. Realising a scheme for decentralised intelligent control that supports fast, autonomous controlled response by vast numbers of devices. This supports self-controlling actions, dynamic topology, dynamic re-routing of power, and self-stabilisation.
3. Development of coordinating actions between multiple aggregators.
4. Development of coordinating actions between aggregators and distribution network operators.
5. Development of coordinating actions between network voltage levels / license areas.

In particular, this ELECTRA intermediate deliverable D6.1 describes the methodology for identification and selection of decentralised control actions and functions for balance and voltage control based on the Web of Cell concept and also includes control specifications applied to six high level Use Cases.

1.1 Assumptions and limitations of the study

The overall objective of the ELECTRA project is to develop radically 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 limitations are not 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. Technologies not feasible now could well be developed in near future, thereby enabling control solutions that seem unrealistic right now. However, present technological limitations will be taken into account to ensure that progress can be achieved.
- **Cost limitations are not considered.** Technological advancement normally leads to significant cost reductions. However, the Task has chosen to consider, but not limit itself to, the present cost limitations in view of future developments.

1.2 Outline of the report

This intermediate deliverable is structured in a way that is intended to make it relatively easy for readers to find the information that is compatible with the information in other tasks of ELECTRA.

The text is divided into the main subjects:

- Balance and Voltage Control
    - *Comprises subjects relevant to both Balance Control and Voltage Control.*
- Balance Control
- Voltage Control

The aforementioned structure is seen in this deliverable and the reader may note that, in part, similar subjects may be repeated in this way. This Intermediate Deliverable comprises the following main topics.

The chapter 2 explains the general methodology for the functional specification of the control functions for the control of the flexibility across the different control boundaries. The proposed control architecture for the new Web of Cell concept should be sufficiently specified to enable further analysis from a control technical point of view as well as from information, communication and business oriented perspectives. The procedure for selecting control functions for Use Cases are also explained.

The chapter 3 describes an overview of objectives, control functions and identified number of control triples for the Main Use Cases. These Control Triples originate from deliverable D5.2, and provide the basis for the intended operation of the Control Functions.

Chapter 4 explains the implementation and selection of control functions for main Use Cases where the control is divided into “Supervisory control” and “Service control”. This chapter describes also the time sequence representations among different actors for intra and inter-cell control. The time sequence diagrams of use cases includes also the functional specifications of control.

The chapter 5 suggests the preference list of Use Cases to be developed further and to be tested in the lab. The conclusions of this intermediate deliverable are presented in the chapter 6. The crucial background work of the task 6.2 for developing control functions have been the technical descriptions of the main use cases which are presented in Annex of this intermediate deliverable.

The final deliverable D6.1 of Electra Task 6.2, due at the end of this Task, will in a similar structure including also the descriptions of the control functions.

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

In the future grid, a shift is expected from central synchronous generators at transmission level to intermittent production units (such as PV panels, wind turbines, etc.) 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.

The above changes were pointed out by the ELECTRA consortium during the project proposal phase. 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 paradigm. During the course of the project a new and novel architecture concept for the future power system has been suggested. The concept was coined “Web-of-Cells” and is described more specifically in [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 Web-of-Cells structure, where the cells are defined as:

- 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 “balance” when it is able to follow the scheduled consumption/generation that was agreed between the BRPs and TSO i.e. when the market parties have ended their balancing activities.
- Cells have adequate monitoring infrastructure installed, as well as local reserves capacity, enabling them to resolve voltage and cell balancing problems locally (for a more detailed description of the concept see D3.1 [2]).

The ELECTRA vision in brief applies a new cell-based concept for solving local problems locally. Even though this cell-based approach is more simple and effective, 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 (automatically activated) restoration reserves by more cost-effective restoration reserves.
- Imbalance netting, system-wide reduction of opposite sign activations.

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.

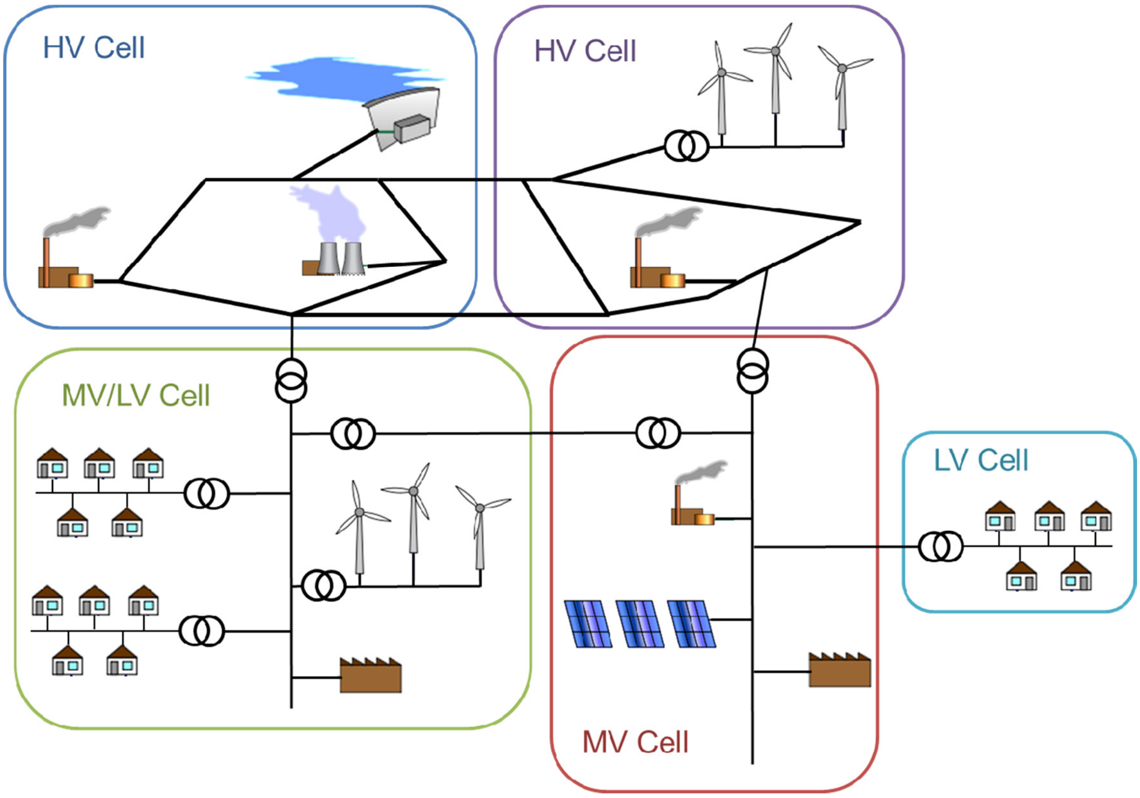

Figure 1 - Schematic example of proposed "Web-of-Cells" architecture. Source: [2]

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 Generic definitions for Balance and Voltage Control

In the scope of ELECTRA, the terms “Balance Control” and “Voltage Control” are defined in a more general way than usual, in order to keep an open mind on all possibilities for grid implementations:

Balance Control

Control loops that serve to keep the power balance between generation and loads, irrespective of the observable used for balance monitoring.

Voltage Control

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 terms "Voltage Control" and "Frequency Control" are a factual description of the present control system, which is specific to AC grids.

The definitions of "Balance Control" and "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, and to all voltage levels (HV, MV, and LV).

2 Methodology

In this chapter, first the general methodology for gaining "*Functional specification of the control functions for the control of flexibility across the different control boundaries*" is explained. Next this methodology is applied to the Sub-Tasks and observables concerning:

- Balance and Voltage Control
- Balance Control
- Voltage Control

2.1 General Methodology

2.1.1 Objectives and Scope

Defining control functions which act across control boundaries for new power system control schemes is a challenging task, as it involves highly technical details of monitoring and control, while at the same time requiring a clear alignment of the involved stakeholders and roles. The proposed control architecture should be sufficiently specified to enable further analysis from a (i) control technical point of view as well as from (ii) information, (iii) communication and (iv) business oriented perspectives.

The Use Case methodology has been selected as a mature approach which facilitates analysis with respect to (ii)-(iii), as outlined in ELECTRA R4.1; yet this approach is not sufficiently structured and technical, and thus not intuitive from an engineering point of view. The approach chosen for this work is therefore an amended Use Case approach that adds further coordinating elements: 1) a common layered systems structure, called Control Topology Levels (CTLs) has been defined across Use Cases, and 2) common categories for times scales, called Control Time Scales (CTSs) are provided. These coordinating elements allow a systematic decomposition of each high-level Use Case into lower-level elements that can be interpreted in terms of decompositions of message sequence diagrams (MSCs) and have meaning beyond individual use cases: CTLs define a high-level clustering of black-box functions (vertical lines in MSC), whereas the CTSs cluster the time scale requirements of interactions/messages (see Chapter 7 for detailed illustration).

Across ELECTRA work packages the so called control triples (comprising Control Aim, System Input Signal and Observable) define a joint scope of power system and applicable flexible resources between WP5 monitoring functions and WP6 control functions, as well as a context in a reference power system topology following the web-of-cells concept.

These concepts and their integration with the Use Case approach are then outlined in the following subsections.

2.1.2 Control Architecture and Design Principles

Before addressing the description of the methodology, it is necessary to reflect on some basic principles reflected in our approach.

2.1.2.1 Control Structure Design

Before a specific controller can be developed, the function and purpose of this controller must be clearly identified. For more complex control systems, the achievement of overall control objectives is usually divided among several control functions. This division and "closing of control loops" is called control structure design. In [7], a systematic approach from process structure to control structure and controller design has been outlined, in application to chemical process control, as a two-stage process. To transfer the chemical process concepts to a power systems context, we can interpret "inventory" correspond with "energy storage" in form of voltage as potential energy or in separation in inertia or batteries, and "production rate" as flow variables such as active and reactive power or current flows.

A. TOP-DOWN ANALYSIS:

- (A.1) Primary Controlled Variables
  - (*) (identify primary controlled variables and self-optimizing variables analysis),
- (A.2) Production Rate and Inventory Control (design for optimal throughput); and

B. BOTTOM-UP DESIGN:

- (B.1) Regulatory Control Layer (stabilization and local disturbance rejection),
- (B.2) Supervisory Control Layer (control structure for primary controlled variables),
- (B.3) Real-time Optimization: optimal setpoints for (*).

The scope of methodology here is primarily on part A, which results in identification of control functions. Steps B.1-B.3 of this design procedure are well supported by control design methods and assume that control objectives and loop pairing (i..e the definition of local control loops by association of measurements with actuators) have been decided.

In other words, control structure design is mainly driven by a top-down and analytical approach. where the outcome is a decomposition of an overall control problem into specific identified control loops. In the methodology pursued here, this outcome of part A manifests in the allocation of "control triples" to specific actors, control resources, and control subsystems. The steps of Part B illustrate that defining control structure comes before optimization, as discussed in Chapter 1.

2.1.2.2 Architectural Principles for Control Structures

Control structure design is facilitated by architectural principles [8] which are summarized here and reflected in the Web-of-Cells control architecture:

I. *Time-scales and execution levels:* A key principle in control structure design is time scale separation: a lower level (faster) control function acts on a set of connected functions to generate a joint behaviour, which effectively creates a single "abstracted" function. We refer to this type of aggregation as the execution level, as an action executed at a faster time scale becomes atomic/invisible at a slower time scale [10].

II. *Encapsulation and Isolation:* It is often desirable to mitigate propagation of disturbances to avoid affecting several process parts. The principle is to encapsulate disturbances by counteracting close to their system entry. We refer to this as disturbance isolation, or encapsulation [9].

III. *Minimal Intervention:* Complete elimination of disturbances can lead to inefficient allocation of control resources, especially if disturbance propagation is not harmful and facilitates smoothing by aggregation of uncorrelated stochastic processes. A resulting minimal intervention principle opposes isolation: to choose controlled variables and objectives such that acceptable disturbances may propagate, while local control only isolates disturbances violating local constraints. An example from power systems: a local power fluctuation may be allowed to propagate through the power system, and should only be mitigated where it may cause an overcurrent or a voltage band violation.

2.1.3 Working procedure for selecting control functions for Use Cases

The procedure for selecting control functions in Use Cases is shown in Figure 2:

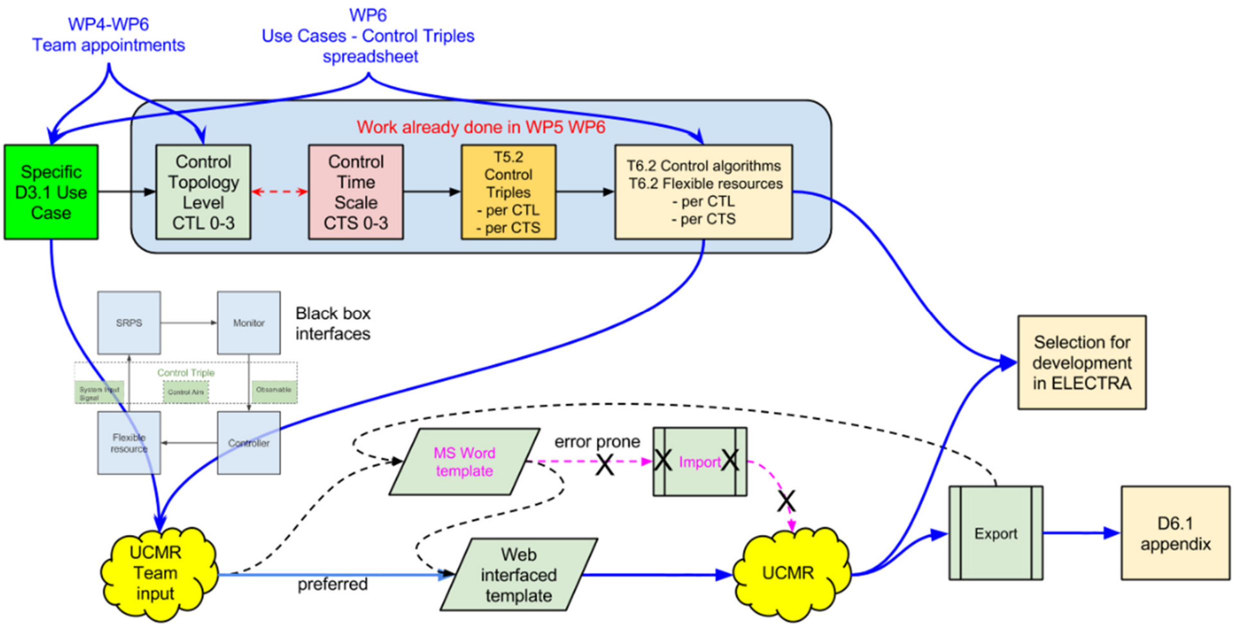

Figure 2 - Working procedure for selecting control functions for a Use Case

The starting point of the control structure definition for detailed Use Cases is the objectives outlined in the High-Level Use Cases from Deliverable D3.1. One purpose of this work is to integrate the outcomes of D5.2, which defines a set of Control Triples containing Observables, for use in WP6. These Control Triples have been defined for specific Control Time Scales (CTS):

- CTS_0: System response
- CTS_1: Primary Level
- CTS_2: Secondary Level
- CTS_3: Tertiary Level

In order to construct multi-layered control functions in accordance with the Web-of-Cells concept in T6.2 which realise the main Use Cases from D3.1 [2], a common layered (control) system structure has been introduced. This layered system structure defines four “Control Topology Levels” (CTLs):

- CTL_0: Physical (single) Device Level
- CTL_1: Flexible (aggregate) Resource Level
- CTL_2: Cell level
- CTL_3: Inter-cell level

Each high-level Use Case was addressed by first formulating a Technical description, which motivates the control structures and formulates the association of its control purposes (high-level objectives) with control triples, control times scales and the decomposition into control topology layers. Based on this, a compact formulation of Detailed Use Case descriptions is developed.

The technical descriptions employ a “control diagram language”, which is defined in the coming section.

The formulation of detailed use cases is directly done in a tool called the "Use Case Management Repository", in which actors and requirements and time sequence of events are formulated to facilitate implementation of the Use Cases in an IT architecture.

2.1.4 General Black Box Functions and interface to other WPs

In order to facilitate information transfer from WP6 to WP3 "*Scenarios and case studies for future power system operation*" and WP4 "*Fully Interoperable Systems*", a general Black Box depiction of a control loop has been agreed as an interface between WPs, as shown in the next figure.

2.1.4.1 General Control Loop with Black Box Functions

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 3 as {Control Aim, Observable, System Input Signal}.

The black boxes can be described as follows.

- The "Monitor" block (function) contains the implementation of the Observable Algorithm
- The "Controller" block (function) contains the implementation of the "Control Aim".
- The "Flexible Resource" represents physical equipment that is able to change the state of the power grid.
- The SRPS block represents, the power grid (model) used.

In order to have a uniform approach towards models, simulations and tests in all WPs, the power grid is implemented as a "Single Reference Power System".

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 observable as a signal represents a physical property within the physical power system.

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.

The physical system input signal provided by the rlexible resource to the power system must be such that it can change the observable value (via causal interactions within the power system). Otherwise, of course, one may end up with a broken control loop that cannot meet its control aim.

The rlexible 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.

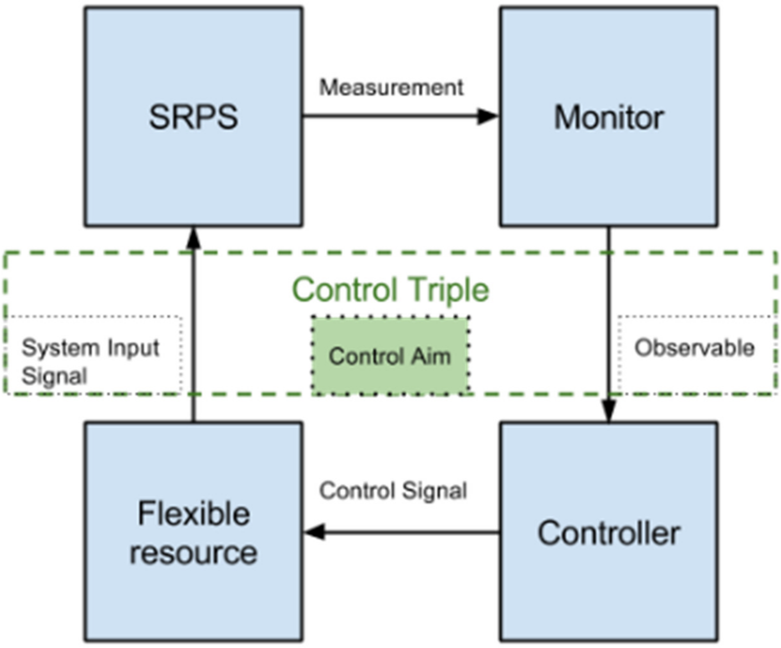

Figure 3 - General Control Loop with Black Box Functions

2.1.4.2 General Control Function

To formally identify a control action, we define the concept of a control action as follows:

Control action:

An **actor** achieves an **objective** by *controlling* an **element** using a **mechanism** subject to **constraints**.

- The control **actor** is from a list of defined actors.
- The control **objective** is described with respect to the system.
- The control **element** means a device/actuator or actor being controlled (other actors or physical resources).
- The control **mechanism** refers to control and coordination mechanisms (please see more descriptions about the control mechanism in the following table).

This definition serves as a backbone of the methodology description. We identify two main parts of this definition:

a. the control context (actors, objectives, control elements, constraints)
b. the control mechanism

As introduced above, in ELECTRA we have a common methodology for identifying the context of control solutions, composed of: Monitor, Controller, Flexibility Resource, and Single Reference Power System (SRPS). We may subdivide this context into a "systems" and a "physical" context:

- Monitors and controllers are **systems** that can interact with each other by exchanging signals and information.
- Physical devices and the power system interact by coupling of physical variables. We refer to these as the **Control Domain.**

Control objectives/aims must be specified *for* a controller (system) and *with respect* to a control domain.

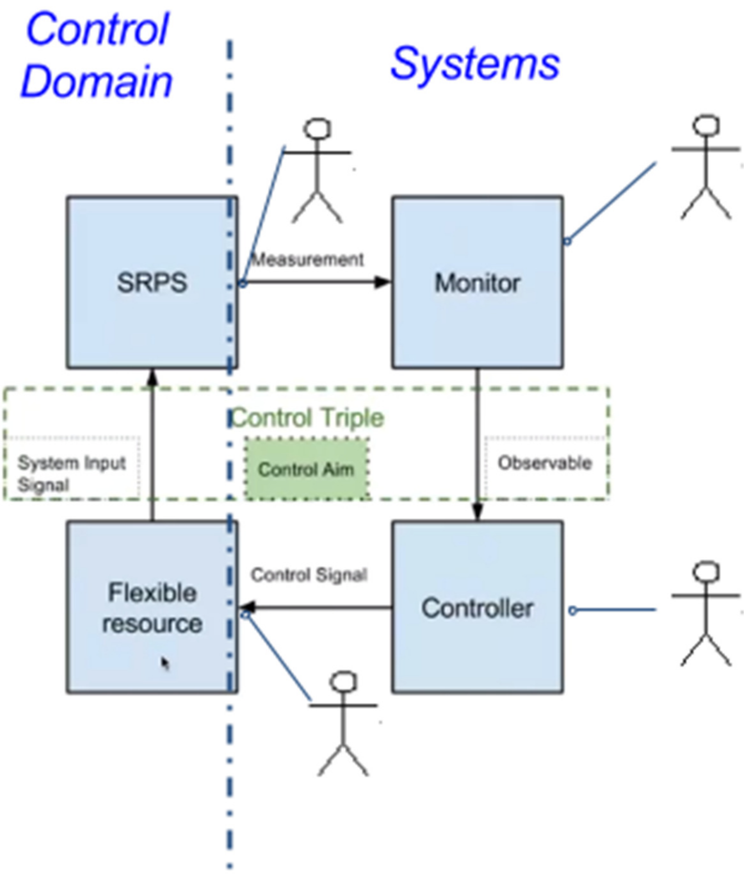

Figure 4 - Control Domain and Systems Domain in General Control Loop with Black Box Functions

Given the definitions above, we can thus specify a control function by providing the information listed in Table 2 (context) and Table3 (function and mechanism).

Table 2: Specification of control actions (Part 1: Context)

Features	Descriptions	Relation to Use Case methodology
Related Use Case	Which (higher level) Use Case is addressed?	Use Case Identifier
Control Actors	Identify the actors involved in the control action.	Actors
Control Objective	Describes the control objective from the system point of view, motivating the control aim.	Objective
Control Triple	The exact control aim, observable, and system input signal for a controller.	Objective
Controller & Control signal	Define the controller and control signal. In case of cascaded control, identify recipient controller.	CTL
Flexibility resource	The (type of) flexibility resource being activated / receiving the	Control Domain

Features	Descriptions	Relation to Use Case methodology
	control signal and providing the system input signal (e.g. ramping of power or energy)	
Physical power system context	Which power system context does the controller apply to? This identifies the control constraints with respect to the power system and cell context (AC/DC, voltage levels, cell type / system boundary type)	Control Domain
Measurement & Monitor	Reference to Monitoring function(s) providing the required observable(s); relate to WP5 results.	Preconditions; Actors; Information (Signal)
Control Time Scale		Requirements

Table 3: Specification of control actions (Part 2: Control Mechanism)

Features	Descriptions	Relation to Use Case methodology
Optimality criterion	How to quantify the “optimality” of the control action. E.g. reference centralized “global” control; social welfare, resource efficiency, user comfort/preferences, maximum use of renewables, . .	Key Performance Indicator
Timing dependencies	Timing dependency & Time scale of control actions and associated system dynamics e.g.: • How fast must the control service react once activated and active (delays/ramping/sampling rate/...)? • In what schedule sequence does this control relate to other control actions? • How long time must the control service stay active (duration)?	Assumptions, Preconditions, Requirements
Assumptions & Prerequisites	Identify general assumptions and dependencies (e.g. with higher & lower level controllers/use cases.) (e.g. consider if/when control reserves are allocated (including market, reserves and dispatch decisions)	Assumptions, Preconditions, Requirements
Control & Coordination mechanisms	How is the control decentralized/distributed? Identify control mechanisms involved in control action and describe in common language / w. illustration; classify related design patterns using the shared taxonomy	New classification item
Communication requirements	Communication requirements (number of endpoints, data rate, reliability, latency) of the controller, in particular in case of a distributed control scheme.	Assumptions, Preconditions, Requirements
Conflicts known/anticipated	Controller conflict is an undesired change of an intended control action as a response to another control action;	New Section: Conflict List

2.1.4.3 Vertical Levels of Control Functions (and Systems) for Use Cases

The control structure of a large-scale power system with distributed energy resources is distributed across several participants, including system operators, aggregators and balance responsible parties, and actual flexible resources. Control systems will be developed independently at these levels and only be able to exchange specifications. For this reason, the overall ELECTRA methodology divides the control into separate levels, termed “Control Topology Levels”. This corresponds to decomposition of the actual “control service” value chain into power system parts with distributed resources.

Controller Topology Levels

The (system) actors are grouped into levels of control, so that the next higher level coordinates regulates or controls actions of the lower control levels. The levels of actors are defined as follows:

- CTL_3: Inter-cell coordination (Cell Group)
  System operators need to coordinate with other system operators with respect to control objectives that affect operations of other cells. Depending on the scope of the respective control objective, such cell groups may be:
    - (energy) market region (for BRC, BSC)
    - synchronous region (setting standards for IRPC, FCC, …)
    - grid control cooperation: a region of cell operators coordinating control objectives (diversity interchange, balance netting) and/or sharing ancillary services (joint procurement, joint activation)
    - local grid branch (subtransmission → distribution)
    - overall coordination entities (such as ENTSO-E)
- CTL_2: Cell
  The level where the cell operator has all responsibility for the associated control objectives; as an area, no Flexible Resources are directly associated with this level.
- CTL_1: Flexible Resource / Aggregators
  CTL_1 is defined as a set (1..*) of Flexible Resources that implements the services required by a Cell operator.
    - Aggregator (within cell / across cells)
- CTL_0: Local (Device) (at DER level)
    - Power Plant
    - Smart House
    - Capacitor bank
    - On load tap changer
    - Synchronous generators
    - Electrical storage

2.1.5 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 and cell inertia, 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 xystem consists of cells that each have a cell monitoring system, which serves both the cell control and the power system monitoring.

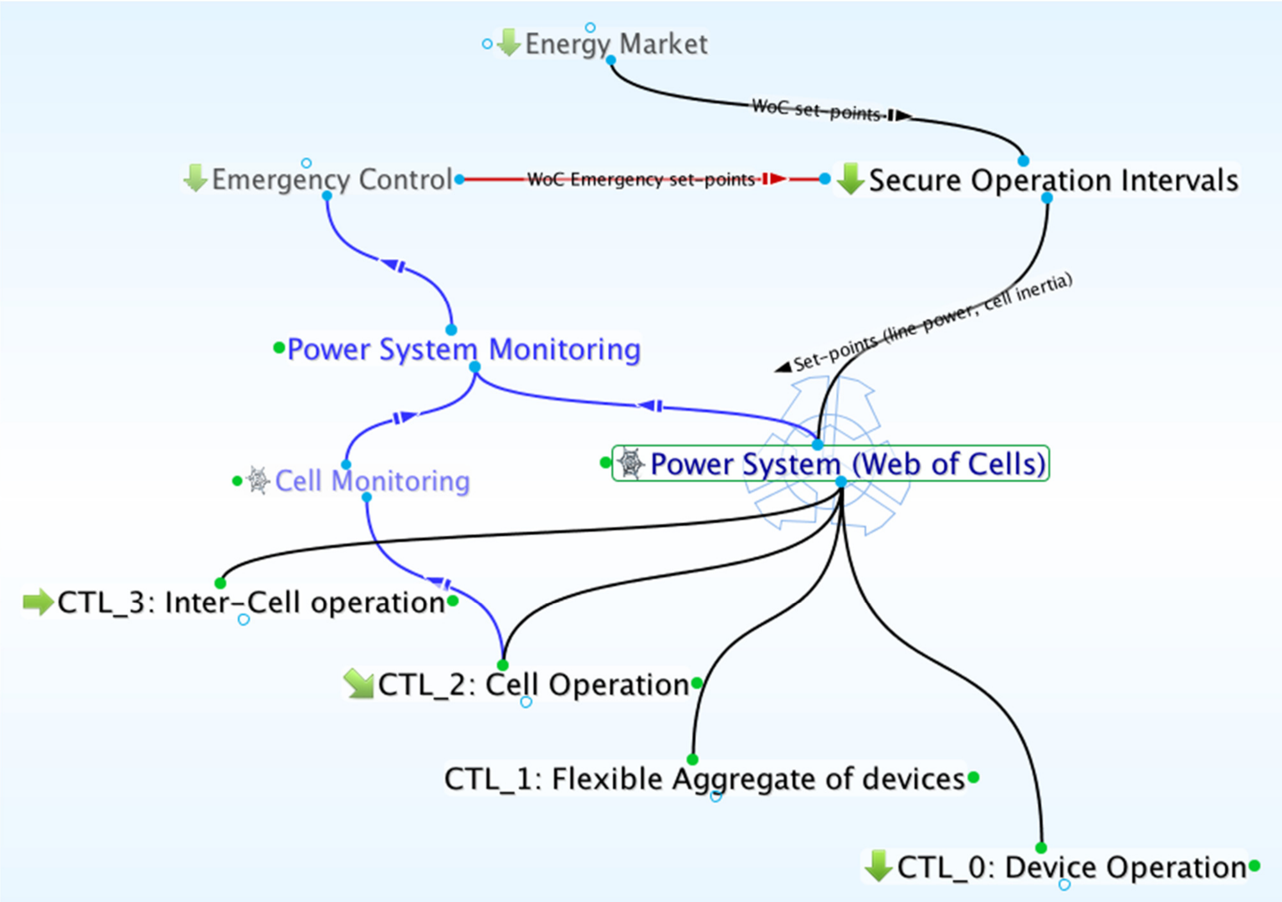

Figure 5 - Control relations in the Web-of-Cells power system

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.

Topology layers of individual Control Functions operate in a certain Control Time Scale (not shown in the Figure):

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

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.

2.1.6 Use Case Composition from Control Functions

As already mentioned in chapter 2.1.4, the Use Case composition is done in two stages:

1. Technical description, and based on this:
2. Use Case description

These are described in more detail in the next paragraphs.

2.1.6.1 Technical description of control functions that support the main Use Case

In order to work out the main Use Cases in detail on basis of the control functions, some examples of control diagrams for a certain Control Topology Level, serving as guidelines, follow in this paragraph.

2.1.6.1.1 Black Box Control Loop

The basic control loop with black box function blocks are described in the next Figure 6.

As the flexible resource and its Input Signal to the SRPS are known here, and directly driven by the Controller, this is in essence a one layer control loop.

Main features:

- One layer

Examples:

- Active Power-Frequency droop control
- Reactive Power-Voltage droop control

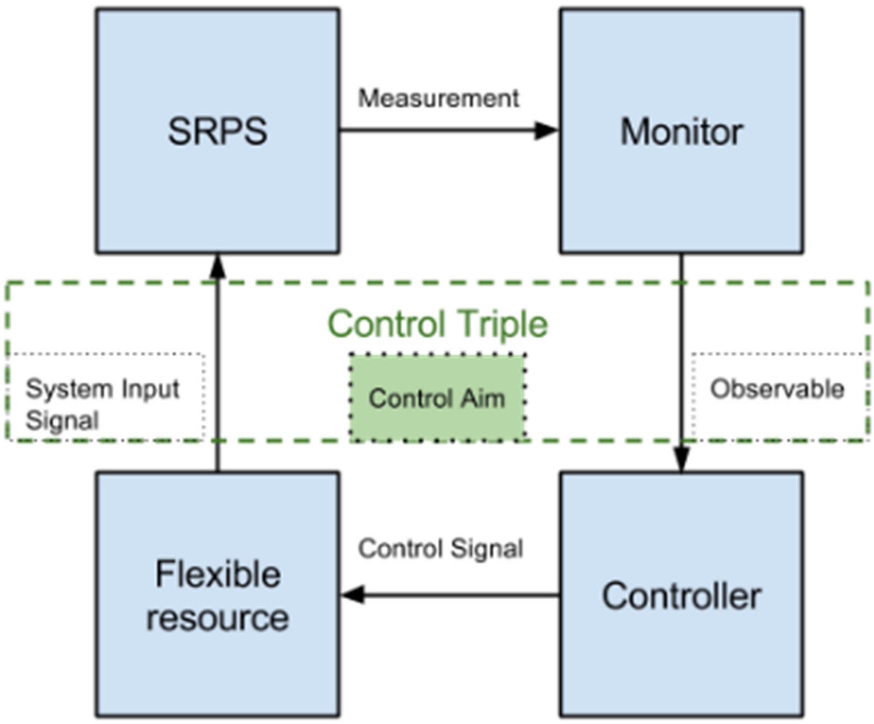

Figure 6 - Black Box Control Loop (one layer)

2.1.6.1.2 Cascaded Control Loop

The top layer of the cascaded control loop is depicted in the next Figure. The rlexible resource and its input signal to the SRPS are not specified yet at this top layer. The control signal enters directly into the SRPS, which therefore must contain either another cascaded Control loop, or a one-layer Black Box control loop with a flexible resource that is able to deliver a physical system input signal that can change the observable value of its control triple.

Main features:

- No rlexible resource at top level.
- In the SRPS, either:
    - another cascaded control loop, or:
    - a black box control loop with rlexible resource

Examples:

- Balance restoration control
- Inertia Steering

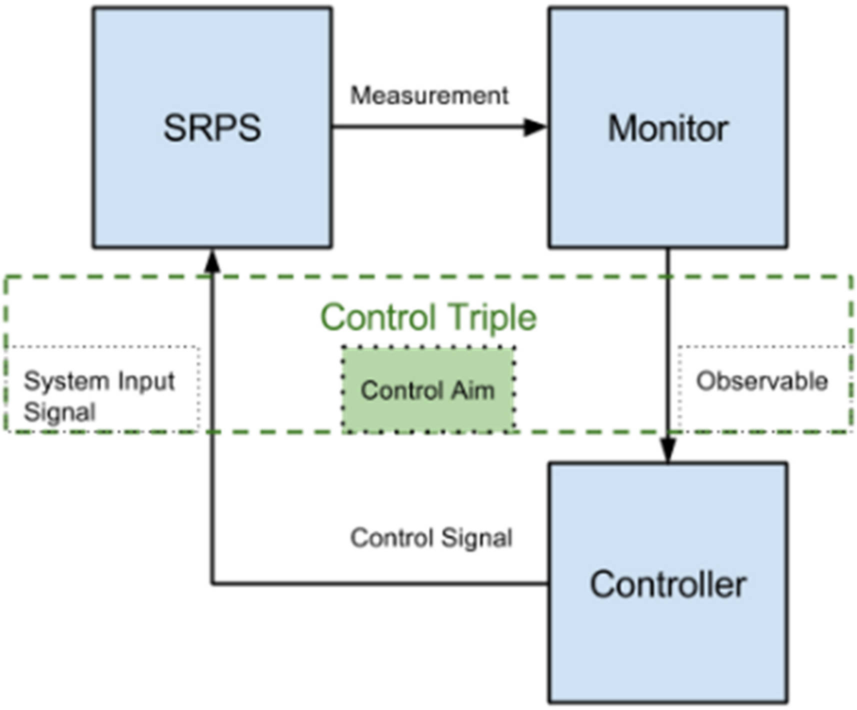

Figure 7 - Cascaded Control Loop (top layer shown)

2.1.6.1.3 Dual Objective Control Loop

The dual objective control loop could be viewed as the "parallel" equivalent of the cascaded control loop. It contains two independent control triples that work in parallel through the same controller, as shown in the next Figure. Each control triple has a system input signal that influences its own observable only, thereby making it possible to achieve its own control aim. The controller tries to achieve some optimum for both Control Aims, and is a composite controller in that sense.

In general, the main control loop is cascaded again, so its control signals give set-points to other control loops at lower Control Topology Levels.

Main features:

- Composite controller
- Cascaded

Examples:

- Post Primary Voltage Control

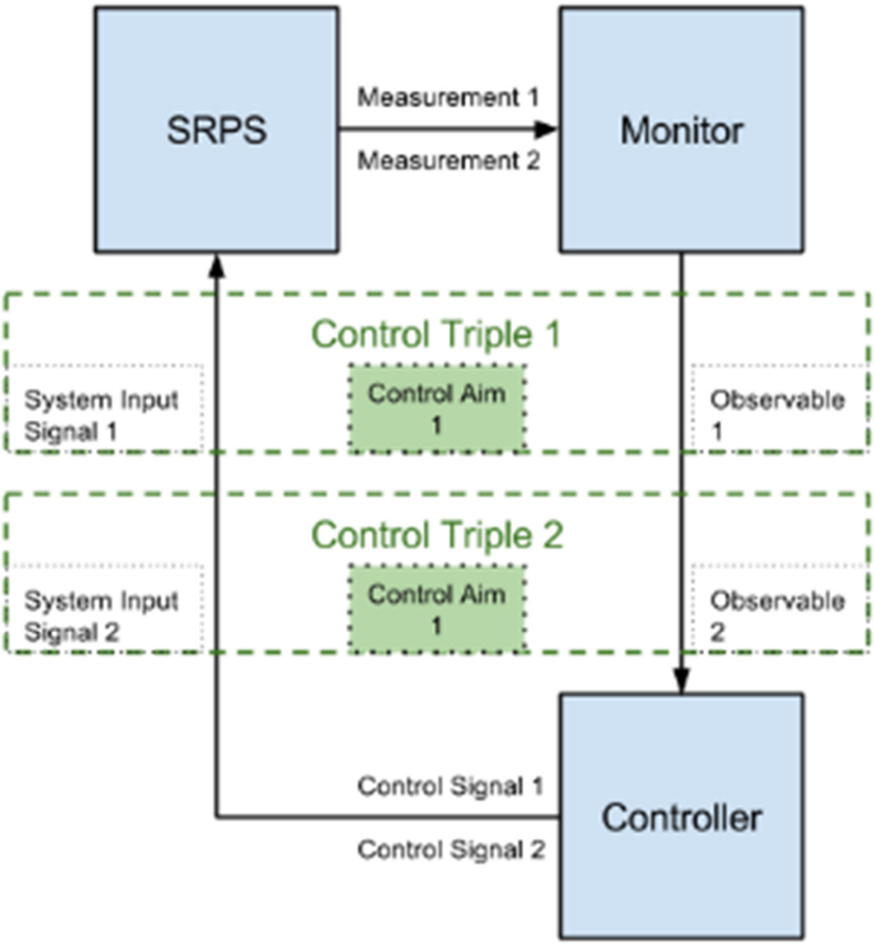

Figure 8 - Dual Objective Control Loop (top layer shown)

2.1.6.2 Composition of Control Aims/triples for control functions

In order to depict the black box control loops needed to serve a certain Use Case, the following steps can be followed:

Step 1. A certain main Use Case is chosen, and
  a. One or more control objective in that Use Case.

Step 2. A Control triple serving the control aim is chosen at an appropriate control topology level.
  a. The list of control triples in the spreadsheet [15] are used as source for these.
    - *The link "Use Case B1.Inertia Response Control" [16] provides an example of a filtered list where only Control Triples for one Use Case are shown.*

Step 3. The Use Case is depicted as a black box control loop, based on the control triple chosen at its control topology level.

Step 4. In case the top level control loop does not specify a physical (tangible) flexible resource, then it is a cascaded control loop, and next:
  a. Step 2 is repeated
  b. Step 3 is repeated
  c. And step 4 (recursive)

Step 5. Continue the process until Step 4 shows physical (tangible) flexible resources

Following this process, one should end up at the lowest control topology level (CTL_0), which is the physical device level.

The list of black box Control Loops drawn in the process each signify a control topology level, together forming a cascaded control loop.

An example of this procedure can be found in Annex: "*Technical description of Main Use Cases*", Chapter: "*Composition of Control Triples for IRPC control functions*".

2.1.6.3 Use Case description of control functions that support the main Use Case

As described in deliverable R4.1, the Use Case methodology is proposed to describe the control functions to be developed within the ELECTRA project.

The Use Case format enables that all actors and the relations and information flows between all actors are clearly defined. Also, the requirements and assumptions for each actor's interactions are identified.

The template used to describe the Use Cases [*EDST 2015 - ELECTRA Use Case Template for Conflict*] [17] is based on the standard Use Case template proposed in IEC-62559-2. This enables the Use Cases to be stored and managed in a use case management repository (UCMR), for follow-up analysis.

For developing the Use Cases, the following methodology was adopted:

- Each main Use Case is broken down into several topology levels, leading to topology level Use Case descriptions.
- If more than one option for a certain topology level Use Case exists, then more than one Use Case description is created.

2.1.6.4 A Taxonomy of Control Mechanisms

This subsection presents a taxonomy of control mechanisms that serves as the basis of the mechanisms used in the ELECTRA project. The taxonomy is shown in Table 5. In general, the control mechanisms are categorized under two relative scopes of control objectives: local and global.

1. Local control objectives
    a. Local control
    no association with higher system level; e.g. local room temperature control
    b. Decentralized control
    addressing a "central requirement"; local control with intended "global" system behavior (designed, engineered, emergent)
2. Global control objectives
    a. Centralized control; direct centralized control
    b. Distributed control
    (joint control objective, employing a coordination pattern, local decision-making; requires communication)
        i. Cascaded hierarchical control - objectives / commands passed down:
            1. Fixed master/slave
            2. Contract net protocol
        ii. peer-to-peer coordination
        iii. "market-based" control/transactive control
            1. Decomposition-based control
            2. Bids, merit-order-based approach
        iv. "quasi-market-based distributed control
            1. Alternating direction method of multipliers (ADMM)

Other important criteria include:

- predictive vs. myopic control: predictive control considers and coordinates with respect to future events and constraints affecting future operating states; ;it is relevant for energy storage and demand-response kick-back effects;
- deterministic vs. stochastic: control objectives and more generally control problems are conventionally formulated in a deterministic framework, but some extensions and alternate formulations define control problems in a stochastic framework
- "hard" vs. "soft" objectives: more recently, in power systems also soft objectives have appeared, where control signals have the form of an incentive, not a fixed response .

In power system control, often several control patterns are combined to achieve a desired overall system behaviour. For example, in the conventional frequency control "cascade":

- primary control: decentralized (1b), myopic, deterministic
- area control:
    - a) distributed control (markets and TSO transmission schedules) for exchange setpoints (2b); then
    - b) secondary control: centralized control (2a)
    - c) hierarchical control/ distributed 'implementation' by BRPs (2b)

tertiary control: market-based control …

With the listed control interaction mechanisms, the following table presents a taxonomy of control mechanisms that contain other information such as the type of objectives, coordination, role allocation and DOW control type.

Table 4:A Taxonomy of Control Mechanism

Relative Scope of Control Aim	Type of Objective	Type of Coordination	Role Allocation	DOW Control Type	Control Interaction
Local	Setpoint	Uncoordinated	fixed roles	Horizontal Control	Uncoordinated Local control
Local	Characteristic	Decentralized	fixed roles	Horizontal Control	Decentralized control
Global	Setpoint	Hierarchical	fixed roles	Vertical Control	Direct centralized control
Global	Setpoint	Hierarchical	fixed roles	Vertical Control	Cascaded hierarchical control
Global	Setpoint	Hierarchical	fixed roles	Vertical Control	Fixed master/slave hierarchical control
Global	Characteristic	Hierarchical	flexible roles	Vertical Control	Hierarchical control with variable master/slave configuration
Global	<any>	Distributed	flexible roles	Horizontal Control	peer-to-peer coordination
Global	Cost function	Distributed	fixed roles	Horizontal Control	transactive control (Market-based control)
Global	Cost function	Hierarchical	fixed roles	Vertical Control	Merit-order-based approach.
Global	Cost function	Distributed	fixed roles	Horizontal Control	Decomposition-based distributed control
Global	Cost function	Distributed	fixed roles	Horizontal Control	Dual-decomposition based control
Global	Probabilistic	Hierarchical	fixed roles	Vertical Control	Indirect control

To further explain for the control mechanisms listed in the above table, some descriptions or examples are given as follows:

Local control: No communication with higher level controller or system operator, e.g., local room temperature control.

Decentralized control: an example is frequency droop control.

Central control: means the system operator centrally dispatches the reference points/objectives to the control elements.

Cascaded hierarchical control: the control problem is decomposed into a control hierarchy where higher level controllers act on lower level controllers by defining setpoints.

Peer-to-peer coordination: In a peer-to-peer configuration, control is distributed among devices in the field. Each device communicates directly with the devices around it, without having to go through a master device. A master may be present for the purpose of monitoring the system and injecting commands, but its presence is not necessary for the peer devices to function. The peer-to-peer coordination allows each device to function both as "master" and "slave".

Market-based control/transactive control[1]: The intent of the transactive control is to reach equilibriums by standardizing a scalable, distributed mechanism via exchanging information about generation, loads, constraints and responsive assets over dynamic, real-time forecasting periods using economic incentive signaling. In Europe, PowerMatcher[2] from TNO is an example of the transactive control for supply and demand matching in electricity networks.

Alternating direction method of multipliers (ADMM)[3] is an algorithm that solves convex optimization problems by breaking them into smaller pieces, each of which is then easier to handle.

2.2 Balance and Voltage Control - Develop autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives

2.2.1 Develop autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives

2.2.1.1 Identify optimal decentralised control actions from High Level Use Cases

The D3.1 HLUCs defined the overall purpose and structure of balance and Voltage Control in the ELECTRA power system. This section clarifies how we arrive from to the breakdown to the distributed control actions to be specified in detailed Use Cases.

The overall principle is to use the proposed control topology levels (section 2.1.5.3) to describe the controller for balance and transmission high level Use Case. The controller is described at each control topology level and the results are presented in sections 2.3.1.2 and 2.4.1.2.

2.2.1.2 Develop/Choose test grid as Single Reference Power System (SRPS)

The Single Reference Power System (SRPS) is a concept proposed in ELECTRA Task T5.1 for facilitating the power system modelling and simulation. In summary, it is a power system description which is independent of the simulation software and the reporting format.

The SRPS definition and selection has been developed by means of an ELECTRA internal survey on currently employed test grids. Please refer to Section 2.2.1 and Chapter "*10. Annex: Summary of SRPS candidates*" of Deliverable D5.2 for details. In T6.2 the SRPS concept is being extended from the basic control loops and simple simulations of T5.2 to larger network models with multiple controllers and where the Web-of-Cells architecture shall be reproduced to some extent.

[1] http://www.gridwiseac.org/about/transactive_energy.aspx
[2] http://www.powermatcher.net/
[3] http://stanford.edu/~boyd/admm.html

2.2.1.3 *Identify Flexible Resources needed*

The flexible resources serving the main Use Cases are summarised in the next table. These originate from an online spreadsheet [18].

Table 5: Flexible Resources needed for Main Use Cases

Flexible Resource	Control Aim	Main Use Case
Controllable loads	Maximise Operation & Maintenance efficiency of aggregated resources [1]	B4-Balance Steering Control
	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
	Mitigate imminent Imbalances [W]	B4-Balance Steering Control
	Substitute aggregated reserves [W]	B4-Balance Steering Control
Energy Storage Systems (ESSs)	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
FACTS	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
Power electronics converter	Achieve a minimum of Reserve Capacity [W]	B3-Balance Restoration Control B4-Balance Steering Control
	Bring frequency back to its set point [Hz]	B3-Balance Restoration Control
	Bring frequency back to its set point in a dynamically optimal way [Hz]	B3-Balance Restoration Control
	Minimise frequency deviations [Hz]	B2-Frequency Containment Control
	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]	B2-Frequency Containment Control
	Secure dynamically optimal power balance via aggregated resources [W]	B3-Balance Restoration Control
	Secure Power Balance by aggregated resources [W]	B3-Balance Restoration Control
Resources participating in PPVC: - Synchronous machines - Converter-coupled sources - Storage devices - FACTS - Controllable loads - Tapped transformers	Proactive over/undervoltages mitigation [V]	T2-Post-Primary Voltage Control

Flexible Resource	Control Aim	Main Use Case
	Restore voltage levels to pre-incident values while optimizing reactive power flows [V]	T2-Post-Primary Voltage Control
Resources with voltage control capabilities with virtual power plants or microgrids	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
Synchronous machine	Inertia Steering at Cell level [s]	B1-Inertia Response Power Control
	Inertia Steering at Synchronous Area level [s]	B1-Inertia Response Power Control
	Minimise transient voltage deviations [V]	T1-Primary Voltage Control
Virtual Synchronous Generator (VSG)	Inertia Steering at Cell level [s]	B1-Inertia Response Power Control
	Inertia Steering at Synchronous Area level [s]	B1-Inertia Response Power Control
	Inertial Response Power Dynamic Control [s]	B1-Inertia Response Power Control
	Minimise stationary frequency fluctuations [Hz/s]	B1-Inertia Response Power Control
	Secure transient frequency stability [Hz]	B1-Inertia Response Power Control

2.2.1.4 Identifying requirements and performance indices for algorithm and controller design

Performance indices $PI_{Observable}$ and $PI_{Controller}$ for observables and controllers are defined in the next paragraphs. From the values for $PI_{Observable}$ and $PI_{Controller}$ found from representative simulations and experiments, requirements will be derived for algorithm and controller design in order to create reliable control loops.

2.2.1.4.1 Performance Index for Observable algorithm design

For an ideal determination of an observable, the proportionality coefficient α between a reference value and a determined value will be 1. Therefore the deviation of this proportionality index from 1 can be used to define a Performance Index $PI_{Observable}$ for the observable algorithm:

$$PI_{Observable} = 1 - max|1 - \alpha|$$

where α is the proportionality index. This is illustrated in the next Figure:

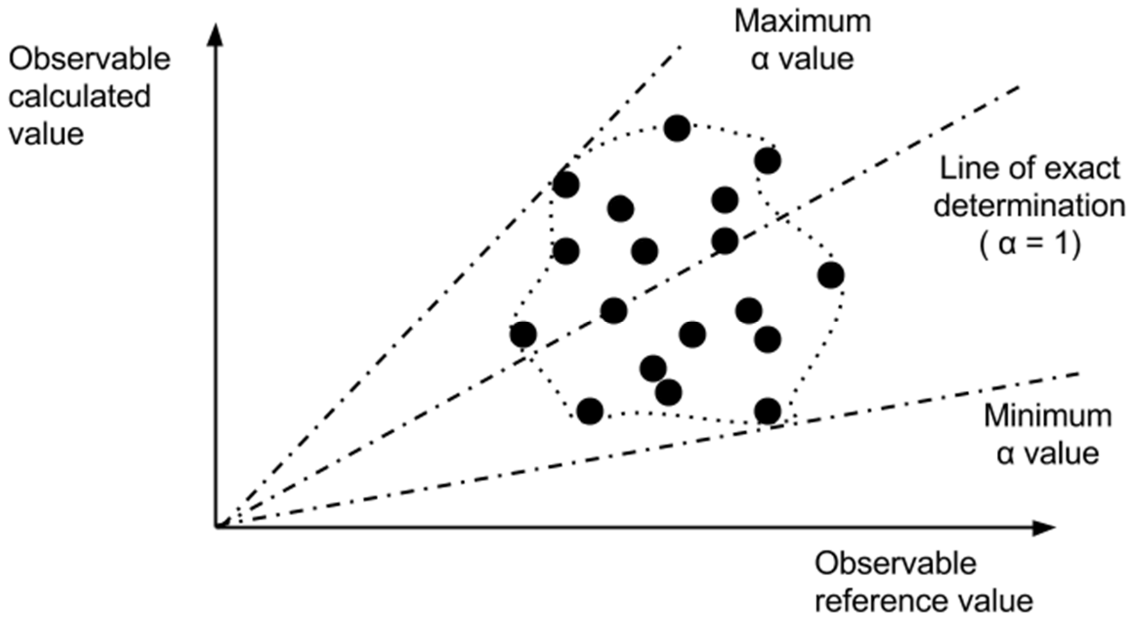

Figure 9 - Performance Index for Observable

From the PI relation it follows that for ideal determination the Performance Index is one.

2.2.1.4.2 Performance Index for Controller algorithm design

For an ideal Controller, the proportionality coefficient α between an Observable set-point and an Observable value will be 1. Therefore the deviation of this proportionality index from 1 can be used to define a Performance Index $PI_{Controller}$ for the Controller algorithm:

$$PI_{Controller} = 1 - max|1 - \alpha|$$

where α is the proportionality index. This is illustrated in the next Figure:

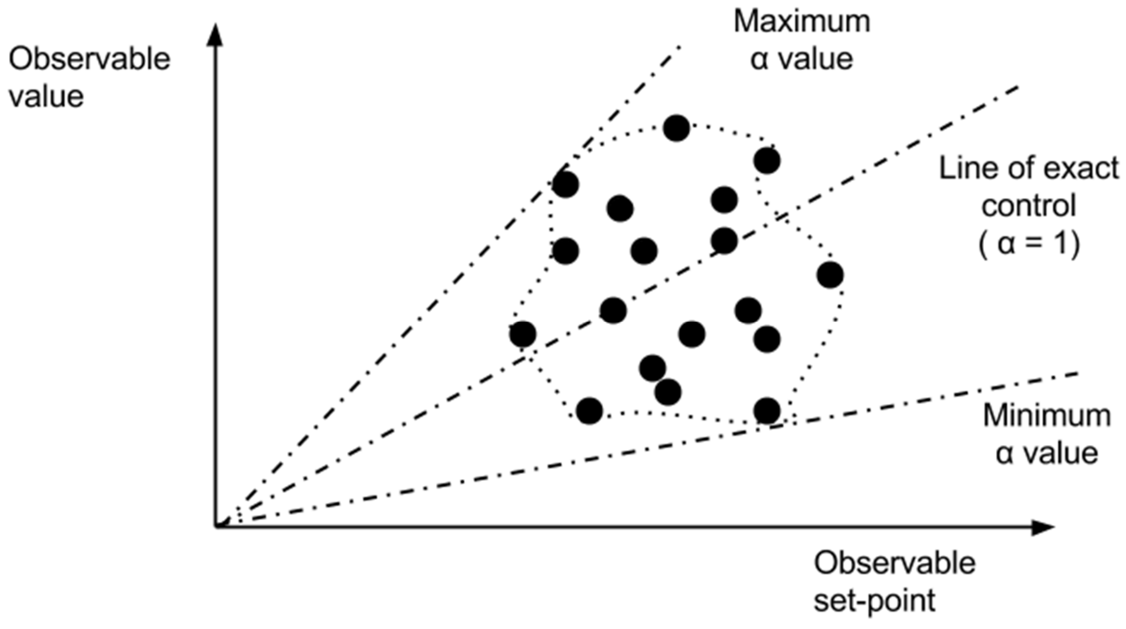

Figure 10 - Performance Index for Controller

From the PI relation it follows that for ideal determination the Performance Index is one.

2.3 Balance Control - Develop autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives

2.3.1 Develop autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives

2.3.1.1 Identify Control Triples needed

The Control Triples needed in the main Use Cases in Balance Control are listed in D5.2, Chapter "*6.1. Control Triples for Balance Control*". These are all needed to serve the main Use Cases.

Table 6 - Control Triples needed for Main Use Cases in 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 response power [W]	Inertial response power set-point of DER [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 its set point in a dynamically optimal way	Frequency [Hz]	Activation of Active Power of aggregated resources [W]

Main Use Case	Control Aim	Observable	System Input Signal
	[Hz]		
	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]

2.3.1.2 *Identify optimal decentralised control actions from Use Cases*

Based on the principle presented in 2.2.1.1, the following table overviews controllers at each control topology level for the four high level balance control Use Cases.

Table 7 - Overview of Balance Control Use Cases described for the four CTLs

Type of Balance Control	Controller Levels / short summary
Inertia Response Power Control (IRPC)	The control is achieved by means of a 4-layered control structure ● CTL3 - Specifying a required amount of inertia J_i from each cell i, which is coordinated among the cell operators in a synchronous region, based on the frequency control objectives stated above. $$\frac{d\omega e}{dt} = \frac{Pm - Pe}{\omega e\,(J1 + J2 + J3)}$$ ● CTL2 - Maintaining a fixed amount of (physical or virtual) inertia J_i provided from each cell (operator). ● CTL1 - Aggregator provides inertia and manages the contracted flexible resources. ● CTL0 - Providing inertia from individual devices
Frequency Containment Control (FCC)	● CTL3 - Coordinate required $\lambda_{i\text{-total}}$ within a synchronous region ● CTL2 - Maintain fixed amount of reserves (λ_i within a Cell)/Observes and regulates in real-time the NPFC or λ_i within a Cell ● CTL1 - Aggregator manages the flexible resources and provides FCC. ● CTL0 - <Primary: locally responds to deviations of the absolute frequency value by injecting/absorbing active power according to a f/P-characteristic, so as to stabilise the frequency to a steady-state value>
Balance Restoration	● CTL3 - Establish schedules and acceptable deviations

Type of Balance Control	Controller Levels / short summary
Control (BRC)	• CTL2 - In real-time restore the cell active power balance with respect to tie-line deviations from the scheduled interchanges, while accounting for ○ Global balancing contributions from FCC + IRPC ○ Acceptable deviations and fluctuations (counter-balancing agreements) • CTL1 - Aggregator tracks cell-reference signal in proportion to reserve share and manages the flexible resources. • CTL0 - <Injecting/absorbing power relative to a scheduled value with participating local device>
Balance Steering Control (BSC)	• CTL3 - Coordinated re-dispatch and adjustment of tie-line schedules • CTL2 - Steer power balance within a Cell (proactively or reactively) in order to replace BRC reserves or mitigate potential imbalances and utilize a real-time market-oriented approach • CTL1 - Schedule-based reference tracking; interact with CTL2 to establish and confirm schedules • CTL0 -

2.3.1.3 Known decentralised Control Actions

By definition, most of the control actions required in balance control are intrinsically decentralised due to the fact that frequency which is a global parameter is regulated with actions spreading from local devices (usually interrelated with fast response) to higher level systems like cells and inter-cell actions. To this end, the analysis is substantially facilitated by the proposed control taxonomy which provides a clear delineation of the boundaries (space and time, i.e. CTLs and CTSs, respectively) in which each decentralised control scheme should be located and specified.

Obviously some of the actions for decentralised control are already in place as today's power systems base their safe operation in control schemes that can be implemented in future power systems. An example of a decentralised control action that can be extrapolated to future power systems is the classic droop control of synchronous generators for the provision of primary frequency control. The same concept is expected to dominate in future systems with large amounts of DER which, via inverters, can provide the system with similar power/frequency regulation.

In summary, this Sub-Task aims to identify those existing control schemes that can also be applicable in future power systems and therefore, it is necessary to identify a list of the control algorithms/systems presently used to provide various types of balance control. A key role in this process is played by the activities of T5.1 which, by means of the analysis and setup of the existing control triples inventory, provides the WP6 consortium with a specific guide regarding present control needs and methods.

2.3.1.4 New decentralised Control Actions

The identification of new decentralised control actions for balance control follows the analysis of control taxonomy and classification of control actions in various topology levels, and it is also combined with the analysis and identification of known control actions. The scope of selecting and/or devising new controllers for decentralised balance (frequency) control is necessary for two reasons:

- New control requirements emerge that can be dealt with exclusively by novel approaches

- Present control schemes are not sufficient to address aspects such as economic optimisations and efficiency, or these methods are oriented to the present generation portfolio, which is expected to change.

Regarding novel control methods, one characteristic example is the decentralised inertia response power control. Currently, the inertia of synchronous generators sufficiently and automatically provides balancing support to power systems during frequency transients. In order to do this, no special arrangement is needed by the system operators in terms of scheduling since inertia is an intrinsic characteristic of the generators and is always available as soon as a generator is operational. However, substituting synchronous generators with DERs that utilise power-electronic inverters entails a reduction of system inertia. This reduction should be compensated with artificially-controlled equivalents in order to enhance transient system stability , and this requirement can only be achieved with new control actions.

In addition to control methods that are entirely new in their concept and implementation, some control architectures and algorithms already put in place will have to be taken into consideration. For instance, the proposed balance restoration control has (BRC), by definition, the same objectives as automatic generation control in today's transmission systems. Currently, the predominant algorithm for achieving this control is the classic PI controller. However effective this controller presently may be, a number of factors impose the need to consider more novel control methods. Such factors may be the stochastic behaviour of generation/load, and efficiency/cost considerations. Therefore, decentralised control techniques that implement new control algorithms may also be considered (e.g. fuzzy systems, H^2 and H^∞ control, Evolutionary Algorithms, and Multi-Agent Systems). These techniques can be used to either improve the performance of existing (known) controllers or to completely substitute them, yet basing their philosophy on the same known and new control triples.

2.4 VoltageControl

The following subsections deal with the application of the general methodology aspects explained in sections 2.1 and 2.2 to voltage control in the Web-of-Cells structure. Control objectives and control functions are identified for the voltage control Use Cases, considering the control topology levels involved, control time scales and control triples, leading to the control algorithms and flexibility resources to be employed.

2.4.1 Develop autonomous control functions that coordinate the action of multiple controllers within a single control boundary according to higher level performance objectives

The methodological steps are the following: after the identification of the involved control triples (or control quadruples if the observable calculation algorithm is also included), the control actions are extracted per control topology level from the Use Cases, to end with the formulation of the known and new decentralised control actions.

2.4.1.1 Identify Control Triples needed

The Control Triples needed in the main Use Cases for Voltage Control are listed in D5.2, Chapter "*6.2. Control Triples for Voltage Control*". These are all needed to serve the main Use Cases.

Table 8 - Control Triples needed for Main Use Cases in 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 [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]
	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]

2.4.1.2 *Identify optimal decentralised control actions from Use Cases*

Based on the principle presented in 2.2.1.1, the following table provides an overview of controllers at each control topology level for the two high level Voltage Control Use Cases.

Table 9 - Overview of Voltage Control Use Cases described in three controller topology level

Type of Voltage Control	Controller Levels / short summary
Primary Voltage Control	• CTL3-Inter cell coordinations • CTL2-Cell operator sets the voltage setpoints to voltage control service providers such as generating unit, synchronous condensers, capacitors. • CTL1-The service provider such as aggregator activates the

Type of Voltage Control	Controller Levels / short summary
	flexible resources. ● CTL0-<The local device responds to the voltage setpoints by adjusting the active and reactive power.>
Post-Primary Voltage Control	● CTL3-By exchanging information with other cells (agreeing on the voltages in the border nodes and power flows in the tie-lines), the Cell operator solves an Optimal Power Flow analysis to determine the voltage set values for the nodes with capacity for voltage control ● CTL2-The cell operator restores the voltage by activating the contracted post-primary voltage control providers. ● CTL1-The post-primary voltage control service providers respond to the activating signals and manage the flexible resources. ● CTL0-The local device responds to the activations from upper level controller, e.g.,aggregator.

2.4.1.3 Known decentralised Control Actions

Voltage control, like balance control, is an essential part of the operation of power systems. At present, the voltage control is organized in terms of a three-step hierarchy: primary, secondary, and tertiary voltage control. Primary voltage control is an automatic control accomplished by fast-acting devices such as automatic voltage regulators of the generation units. The response time of primary voltage control is nearly instantaneous (a few seconds). The goal of primary voltage control is to act over the reactive power injection into the point of interconnection of the device. The secondary voltage control (SVC) supervises and coordinates the primary voltage control within an area. The purpose of secondary voltage is to carry out modification in real time and in a coordinated manner so that a near-optimal operational situation can be achieved. The response time of the secondary control is a matter of minutes (200 to 300 s). The tertiary voltage control represents an optimization of the secondary voltage control. It is usually based on a global system optimization which calculates updated voltage set-points for the regional voltage controllers associated to SVC while minimizing reactive power losses. It is completed in a time scale ranging from 10 mins to 30 mins.

As discussed in ELECTRA project deliverable D3.1, the evolution of power grids will imply the development of new architectures based on the coordination and mutual collaboration of modular structures called cells. As a consequence, two types of voltage control Use Cases are identified in the ELECTRA project: primary voltage control and post-primary voltage control (with the latter substituting both the traditional secondary and tertiary voltage control).

Primary voltage control (PVC) is a fast process (sub-seconds to several seconds) executed locally such as controlling the production, absorption, and flow of reactive power at different voltage levels. Post-primary voltage control (PPVC) is intended to replace the present secondary and tertiary voltage control by a decentralized control, located at a cell level. Each cell is responsible for its own voltage while a close coordination between cells guarantees the provision of PPVC service between neighboring cells.

A detailed description of these two voltage Use Cases (PVC and PPVC) is presented in D3.1, Chapter 5.1 and 5.2. From the report, it is seen that some known solutions used in the conventional voltage control schemes will still play important roles in the ELECTRA project. In PVC, these solutions include synchronous generators (equipped with automatic voltage regulators) that provide the basic means of voltage control and additional means such as synchronous condensers, shunt capacitors, shunt reactors, static var compensators, and regulating transformers. In PPVC, the known methods include market-based approaches, optimal power flow analysis etc. which will continue to be employed in the Web-of-Cells architecture proposed within the ELECTRA project.

2.4.1.4 New decentralised Control Actions

This subsection firstly summarizes the new voltage control resources and then describes the novel control methods.

It is known that the evolution of power systems entails a decentralization process with fewer available large power plants for voltage and reactive control. Instead, increasing integration of distributed energy resources (DER) and available monitoring devices in the power systems make voltage services provided by DERs possible. Besides these inverter-based reactive provision resources (DER), some new voltage control resources including on load tap changer transformers, static synchronous compensators (STATCOM) and Static VAR compensators are currently available for power systems operation and some are proposed for distribution network operation, e.g., medium and low voltage cell operation.

Regarding novel control methods, it is discussed in [12] that unlike in the conventional power system where voltage services are provided by controlling large-size units, voltage services will be provided by a large quantity of small controllable DERs, which makes the management system rather complex. Thus proper aggregating and coordinating schemes for DER portfolios are required to effectively facilitate control solutions to individual problematic distribution feeders. It is summarized in [12] that the proposed coordinating schemes for DERs include: autonomous control, peer-to-peer coordination, hierarchical control and centralized control. Furthermore, a technical metrics and market adopted metrics are presented in study [12] to assess the voltage control solutions in view of deployment. In addition, a functioning and effective marketplace [12] might be established to fulfill the increasing requests from cell operator and DER owners for information exchange and accommodation of various services. Besides the methods summarized in [12], the authors of [13] casted the voltage regulation as an optimization problem where the objective is to minimize the losses in the network subject to constraints on bus voltage magnitudes, limits on active and reactive power injections and transmission line thermal limits. A sufficient condition is provided under which the optimization problem can be solved via its convex relaxation.

3 Control Triples for the high level Control Functions of the main Use Cases

The procedure followed for systematically selecting potential control functions for the main Use Cases is explained in detail in chapter 2.1.5. Working procedure for selecting control functions for Use Cases. These control functions serve as basic building blocks for implementing the high level objectives of the main Use Cases. This means that from these several architectural options and combinations may follow to implement these high level Use Case objectives .

In the next table, an overview of objectives, control functions and identified number of Control Triples are given for the main Use Cases. The Control Triples column lists the number of identified Control Triples covering the control function, while the Control Topology Level column lists the Control Topology Levels at which they operate, and the Control Time Scale column their characteristic time scales.

These control triples originate from deliverable D5.2, and provide the basis for the intended operation of the control functions.

Table 10 - Objectives, Control functions and identified number of Control Triples for the Main Use Cases.

LEGEND:
CTL_0: Physical (single) Device Level, CTL_1: Flexible (aggregate) Resource Level, CTL_2: Cell level, CTL_3: Inter-cell level
CTS_0: System response, CTS_1: Primary Level, CTS_2: Secondary Level, CTS_3: Tertiary Level

Use Case	Use Case objectives	Control function	Control Topology Level	Control Time Scale	Control Triples
B1-Inertia Response Power Control	a. The limitation of rate of change of frequency, dfdt, to a maximum allowed value and thus maintaining a certain level of frequency stability, during contingencies b. Limiting the frequency deviations during normal operation to a specified range (fmin< f < fmax) c. Supporting frequency containment control (FCC) until FCC is fully activated	Maintaining a fixed amount of (physical or virtual) inertia Ji provided from each cell (operator)	CTL_2	CTS_3	2
		Providing inertia from aggregated units	CTL_1	CTS_0	2
		Providing inertia from individual units	CTL_0	CTS_0	2
				CTS_1	1
		Specifying a required amount of inertia Ji from each cell i, which is coordinated among the cell operators in a synchronous region, based on the frequency control objectives: dωdt=(pm-pe)ω1nJi	CTL_3	CTS_3	2
B1-Inertia Response Power Control Total					9
B2-Frequency Containment Control	a. Response to frequency deviations b. Regulation of Network Power Frequency Characteristic	Determine available reserves capacity based on procurement at cell levelRegulate the NPFC contribution of a cell to the overall system characteristic by adjusting the resource's parameters	CTL_2	CTS_3	1
		Establish NPFC at system level and determine contributions of each cell	CTL_3	CTS_3	2
		Respond to frequency deviations by monitoring frequency centrally and controlling individual devices	CTL_1	CTS_1	1

		(active power or on/off set points)			
		Respond to frequency deviations by monitoring frequency locally and controlling device state (active power or on/off set point)	CTL_0	CTS_1	1
B2-Frequency Containment Control Total					5
B3-Balance Restoration Control	a. Detection of Balance Restoration error b. Determination of state of cell c. Definition of restoration reserves merit order d. Determination of activation orders e. Sending of activation orders to restoration reserve providers f. Activation and monitoring of reserves	Establish schedules and acceptable deviations	CTL_3	CTS_2	2
				CTS_3	1
		In real-time, restore the cell active power balance with respect to tie-line deviations from the scheduled interchanges, while accounting for global balancing contributions from FCC and IRPC	CTL_2	CTS_2	2
				CTS_3	1
B3-Balance Restoration Control Total					6
B4-Balance Steering Control	a. Substitution of implemented reserves after imbalance incidents (reactively) b. Mitigation of imminent imbalances (proactively)	Determine available capacity of BSC resources via procurement phase	CTL_3	CTS_3	1
		Proactively mitigate imminent imbalancesReactively substitute BRC reserves already active from previous actionsMinimise Operation and Maintenance Cost of deployed resources	CTL_2	CTS_3	3
B4-Balance Steering Control Total					4
T1-Primary Voltage Control	a. maintain the required value of voltage at a measurement point b. enable selection of either active or reactive power as a control signal for voltage regulation.	The local device responds to the voltage setpoints by adjusting the active and/or reactive power.	CTL_0	CTS_1	7
		The service provider such as aggregator activates the flexible resources.	CTL_1	CTS_1	1
T1-Primary Voltage Control Total					8
T2-Post-Primary Voltage Control	a. restore voltage levels to pre-incident values while optimizing reactive power flows (minimizing the losses). b. mitigate over/undervoltages by the activation of reserves in advance while optimizing reactive power flows.	Coordination of voltage levels with neighbouring cells when a congestion occurs or there is unavailability of own resources in the cell under analysis	CTL_3	CTS_2	4
				CTS_3	4
		Keeping (restoring) node voltage levels within the established band while optimizing reactive power flows (minimizing the losses) at cell level	CTL_2	CTS_2	4
				CTS_3	4
T2-Post-Primary Voltage Control Total					16
Grand Total					48

The following table lists in detail which control triples could be used for constructing each control function. Not all of the control triples may be used, depending on preferences and flexible resources present in the specific power system that is considered.

Table 11 - Objectives, Control functions and identified Control Triples for the Main Use Cases in ELECTRA (several subsequent table parts)

Control function	Control Aim	Measurement	Observable	Flexible Resource	Control Signal	System Input Signal
Maintaining a fixed amount of (physical or virtual) inertia Ji provided from each cell (operator)	Inertia Steering at Cell level [s]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Actual Cell Inertia time constant [s]	Synchronous machine	Vector of Inertia Constant values of individual resources	Deployment of a collection of slow starting Cell resources which exchange inertial response power [0/1]
				Virtual Synchronous Generator (VSG)	Vector of parameters determining Inertia Constant of individual devices	Deployment of inertial response power in a collection of converter interfaced resources [0/1]
Providing inertia from aggregated units	Minimise stationary frequency fluctuations [Hz/s]		Actual frequency of node voltage [Hz]	Virtual Power Plant (VPP)	Activation vector of resources based on a match between availability and demand for inertial response power.	Inertial response power [W]
	Secure transient frequency stability [Hz]				Activation vector of resources	Inertial response power [W]
Providing inertia from individual units	Inertial Response Power Dynamic Control [s]		Inertial time constant of DER [s]	Virtual Synchronous Generator (VSG)	Inertial time constant set-point [s]	Inertial response power [W]
	Minimise stationary frequency fluctuations [Hz/s]		Actual frequency of node voltage [Hz]		PWM input range [-1, +1]	Inertial response power [W]
	Secure transient frequency stability [Hz]		Actual frequency of node voltage [Hz]		PWM input range [-1, +1]	Inertial response power [W]
Specifying a required amount of inertia Ji from each cell i, which is coordinated among the cell operators in a synchronous region, based on the frequency control objectives: dωdt=(pm-pe)ω1n Ji	Inertia Steering at Synchronous Area level [s]		Actual Synchronous Area inertia [s]	Synchronous machine	Vector of Inertia Constant values of individual Cells	Deployment of a collection of slow starting Cell resources which exchange inertial response power [0/1]
				Virtual Synchronous Generator (VSG)		Deployment of inertial response power in a collection of converter interfaced resources [0/1]

B2-Frequency Containment Control						
Control function	**Control Aim**	**Measurement**	**Observable**	**Flexible Resource**	**Control Signal**	**System Input Signal**
Determine available reserves capacity based on procurement at cell levelRegulate the NPFC contribution of a cell to the overall system characteristic by adjusting the resource's parameters	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Actual Network Power Frequency Characteristic (λi) [W/Hz]	Power electronics converter	Vector of NPFC parameter values of individual resources	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
Establish NPFC at system level and determine contributions of each cell	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]		Cell Energy production in standard time interval [Ws] Web-of-Cells Energy production in standard time interval [Ws]	Power electronics converter	Vector of NPFC values of individual Cells	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
Respond to frequency deviations by monitoring frequency centrally and controlling individual devices (active power or on/off set points)	Minimise frequency deviations [Hz]		Frequency [Hz]	Power electronics converter	Vector of Active Power deviations (ΔP)	Active Power of aggregated resources [W]
Respond to frequency deviations by monitoring frequency locally and controlling device state (active power or on/off set point)	Minimise frequency deviations [Hz]		Frequency [Hz]	Power electronics converter	PWM input range [-1, +1]	Active power of Synchronous Generator [W]

B3-Balance Restoration Control						
Control function	**Control Aim**	**Measurement**	**Observable**	**Flexible Resource**	**Control Signal**	**System Input Signal**
Establish schedules and acceptable deviations	Achieve a minimum of Reserve Capacity [W]	Flexibility offer(s)	Availability of Flexible Resources [W]	Power electronics converter	Vector of parameters determining reserve capacity of individual resources	Aggregated active power capacity [W]
	Bring frequency back to its set point in a dynamically optimal way [Hz]	Sampled voltage 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Frequency [Hz]		Vector of Active Power deviations (ΔP) to individual resources	Activation of Active Power of aggregated resources [W]
	Secure dynamically optimal power balance via aggregated resources [W]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Cell power balance [W]			
In real-time, restore the cell active power balance with respect to tie-line deviations from the scheduled interchanges, while accounting for global balancing contributions from FCC and IRPC	Achieve a minimum of Reserve Capacity [W]	Flexibility offer(s)	Availability of Flexible Resources [W]	Power electronics converter	Vector of parameters determining reserve capacity of individual resources	Aggregated active power capacity [W]
	Bring frequency back to its set point [Hz]	Sampled voltage 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Frequency [Hz]		Vector of Active Power deviations (ΔP) to individual resources	Activation of Active Power of aggregated resources [W]
	Secure Power Balance by aggregated resources [W]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Cell power balance [W]			

B4-Balance Steering Control						
Control function	**Control Aim**	**Measurement**	**Observable**	**Flexible Resource**	**Control Signal**	**System Input Signal**
Determine available capacity of BSC resources via procurement phase	Achieve a minimum of Reserve Capacity [W]	Flexibility offer(s)	Availability of Flexible Resources [W]	Power electronics converter	Vector of parameters determining reserve capacity of individual resources	Aggregated active power capacity [W]
Proactively mitigate imminent imbalances. Reactively substitute BRC reserves already active from previous actionsMinimise Operation and Maintenance Cost of deployed resources	Maximise Operation & Maintenance efficiency of aggregated resources [1]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Operation & Maintenance efficiency of aggregated resources [1]	Controllable loads	Vector of On/Off state and Active Power set point of resources	Deployment of Active Power of aggregated resources [W]
	Mitigate imminent Imbalances [W]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Active power of aggregated resources [W]			
	Substitute aggregated reserves [W]	Sampled voltage and current 50 Hz nominal 25 kHz (+/- 0.04 ms = +/- 0.2% timing error) 512 bits (+/- 0.2% amplitude error)	Active power of aggregated resources [W]			

T1-Primary Voltage Control						
Control function	Control Aim	Measurement	Observable	Flexible Resource	Control Signal	System Input Signal
The local device responds to the voltage setpoints by adjusting the active and/or reactive power.	Minimise transient voltage deviations [V]	Current waveforms	Current in DQO axis [A]	Power electronics converter	PWM signals	complex power of non-rotating generators [VA]
		Line-to-line voltage waveforms	Actual node voltage [V]	Controllable loads	Curtailment order / Shedding command	Active power of the controllable loads [W]
				Energy Storage Systems (ESSs)	PWM signals	Fast storage active and reactive power [VA]
				FACTS	Signals to the thyristors drivers	Reactive power of FACTS [VAr]
				Synchronous machine	Field current of the excitation system	Reactive power of synchronous generator/compensator [VAr]
					Speed/Mechanical torque	Active power of Synchronous Generator [W]
			Voltage in DQO axis [V]	Power electronics converter	PWM signals	complex power of non-rotating generators [VA]
The service provider such as aggregator activates the flexible resources.	Minimise transient voltage deviations [V]	Line-to-line voltage waveforms	Actual node voltage [V]	Resources with voltage control capabilities with virtual power plants or microgrids	According to the resource type	complex power of aggregated resources (microgrids, VPPs...) [VA]

T2-Post-Primary Voltage Control						
Control function	**Control Aim**	**Measurement**	**Observable**	**Flexible Resource**	**Control Signal**	**System Input Signal**
Coordination of voltage levels with neighbouring cells when a congestion occurs or there is unavailability of own resources in the cell under analysis	Proactive over/undervoltages mitigation [V]	3-phase voltage & current waveforms	Collection (vector) of complex power [VA]	Resources participating in PPVC: - Synchronous machines - Converter-coupled sources - Storage devices - FACTS - Controllable loads - Tapped transformers	According to the PPVC resource type: - Field current of the excitation system (synchronous machines) - PWM signal (converter-coupled sources, ESS) - Signals to thyristor drivers (FACTS) - Curtailment/shedding commands (controllable loads) - Voltage level activation command (OLTC)	Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]
		3-phase voltage waveforms	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]	3-phase voltage & current waveforms	Collection (vector) of complex power [VA]			Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]
		3-phase voltage waveforms	Collection (vector) of voltage phasors [V,rad]			Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]
Keeping (restoring) node voltage levels within the established band while optimizing reactive power flows (minimizing the losses) at cell level	Proactive over/undervoltages mitigation [V]	3-phase voltage & current waveforms	Collection (vector) of complex power [VA]	Resources participating in PPVC: - Synchronous machines - Converter-coupled sources - Storage devices - FACTS - Controllable loads - Tapped transformers	According to the PPVC resource type: - Field current of the excitation system (synchronous machines) - PWM signal (converter-coupled sources, ESS) - Signals to thyristor drivers (FACTS) - Curtailment/shedding commands (controllable loads) - Voltage level activation command (OLTC)	Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]
		3-phase voltage waveforms	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]	3-phase voltage & current waveforms	Collection (vector) of complex power [VA]			Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]
		3-phase voltage waveforms	Collection (vector) of voltage phasors [V,rad]			Active power set-points to DERs [W]
						Optimal voltage set-points to DERs [V]

4 Implementation of Control Functions for main Use Cases

4.1 Stepwise procedure for architectural control options

In order to generate innovative architectural control options for the control functions described in the main Use Cases, a stepwise procedure is followed, which is briefly described in the next paragraphs.

4.1.1 Fundamental implementation choices for specific high level Control Aims of Use Cases

As a mockup example, the use case of Balance Restoration Control is considered. Its main objective is:

D3.1 Objective : Power balance within the cell as well as power exchange with other cells is restored to its scheduled value after activating Balance Restoration Reserves

Considering the type of grid area, there are the next options for the cells:

1. Synchronous AC cells
2. DC cells
3. Asynchronous AC-DC cells (multiple synchronous AC cells and DC cells)

The cell power balance could be reflected in the State of Charge (SOC) of a dedicated cell storage device, or be calculated from tie-line power flows in absence of a dedicated cell storage device:

1. No dedicated cell storage
2. Dedicated cell storage

Storage cannot simply be regarded as either generation or load, because it can only can exchange power as long as its State of Charge (SOC) is in between zero and 100%. At 100% it only can start off as a generator, and at 0% only as a load. In between it can do both.

The SOC deviation of a dedicated cell storage can be a measure of the cell power balance when it's charging and discharging is dictated by a physical process, like e.g. a raise of voltage of shift of AC phase, and that physical signal is caused by an deviation of the cell power balance.

The options above lead to six potential combinations, where the main observables involved are:

1. System Power Balance [W]
2. Cell Power Balance [W]
3. Cell Power Exchange [W]

These Observables must be defined separately for AC and DC cells.

For the case of Synchronous AC cells, some potential combinations are listed in the next table:

Table 12 - Fundamental implementation choices of observables for {System Power Balance [W], Cell Power Balance [W], Cell Power Exchange [W]}

	Synchronous area of multiple cells				
Conditions	System Power Balance	Cell Power Balance		Cell Power Exchange	Sub Case
	Frequency deviation	SUM of measured tie-line flows	SOC deviation of local stores	RMS of tie-line power flow deviations	
	$\Delta f_{Synchronous}$	ΔP_{SUM_Ties}	ΔSOC_{Stores}	ΔP_{RMS_Ties}	
AC cells storage	?	x		x	BRC1
Controlled tie-line power flows	?		x	x	BRC2
General case	?	x	x	x	BRC3

4.1.2 Identification of architectural options for each specific high level Control Aim

Variants are identified that can be documented as a tuple {Control Loop Architecture option, Controller Paradigm, Resource Activation Mechanism}, as shown in the next table. Not all permutations may be feasible.

Table 13 - Architectural options for {Control Loop Architecture option, Controller Paradigm, Resource Activation Mechanism}

Sub Case Variant	Control Loop Architecture		Controller Paradigm (Action)				Resource Activation Mechanism	
	Monitor	Controller	PI(D)	MPC	Rule (Policy) based	Optimiser	Decision	Continuous
BRC1.1	Central	Decentral					Direct dispatch	
	Central	Decentral					Indirect dispatch	

4.1.3 Selection of innovative architectural options for implementation and testing

For the selection of innovative control options, the following criteria are taken into consideration :

- Level of innovation
- Assessed stability
- Feasibility (in 2030)
- Potential conflicts with other controls
- Cyber security
- Robustness and resilience
- Predicted cost in 2030

4.1.4 Documentation of selected variants

The selected variant are documented in the full IEC 62559 template, and next uploaded in a use case management repository.

- A sequence diagram shows explicitly a sequence or timeline of discrete actions
- A CLD may be more clear for 'instantaneous and continuous' control
- In both cases the representations must focus on the needed black-box functions and interactions i.e.
  - Functions are depicted as vertical timelines in the MSD: black-box functions are depicted as actors or as a segment of a vertical timeline
  - Functions are depicted as blocks in the control loop block diagram

4.1.5 Design

The selected variants are further described in Time Sequence Diagrams (TSDs), as shown in mockup example in the next Figure 11:

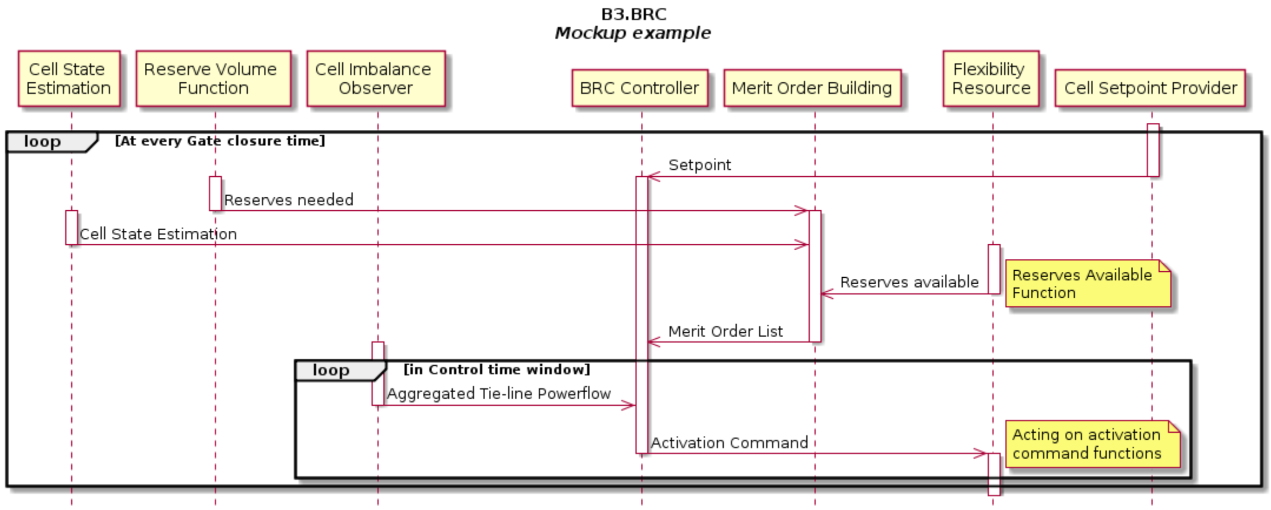

Figure 11 - Mockup example of Time Sequence Diagram with high level control Functions.

On the top horizontal row, the identified Functions are placed. These are further detailed as shown in the next Table 14:

Table 14 - Detailed description format for high level control Functions.

Function	Operation description	Input	Action	Output
Cell State Estimation	<...>	<...>	<...>	<...>
Reserve Volume Available	<...>	<...>	<...>	<...>
Reserve Volume required	<...>	<...>	<...>	<...>
Merit Order Building	<...>	<...>	<...>	<...>
Cell (Im)balance Observer	<...>	<...>	<...>	<...>
BRC Controller	<...>	<...>	<...>	<...>
Setpoint Provider	<...>	<...>	<...>	<...>

Chosen individual solutions as well as combinations of solutions are further implemented and tested in simulation with the aid of Control Triples.

This if further worked out in the Annex: “Conceptual Use Case variants overview and selection for voltage and balance control”.

4.2 Supervisory Control functions and Service Control functions

In order to chose between the most appropriate depiction of control functions, a distinction is made between supervisory control functions and service control functions.

- Supervisory control functions are in general comprised of sequential steps and decisions, and therefore can be adequately described by a time sequence diagram (TSD).
- Service control functions in general are automatic and continuous control loops where control loop parts with their signals are interacting concurrently. No decisions are taken, and there are no sequential steps. This type of control function is best described by a control loop (block) diagrams (CLD).
- Supervisory control functions usually are at the highest control topology level (CTL) of a control function.
- Service control functions are usually present at the lowest CTLs of a control function, and are the physical enablers of functions at higher CTLs..

The basic idea is illustrated in the next Figure 12:

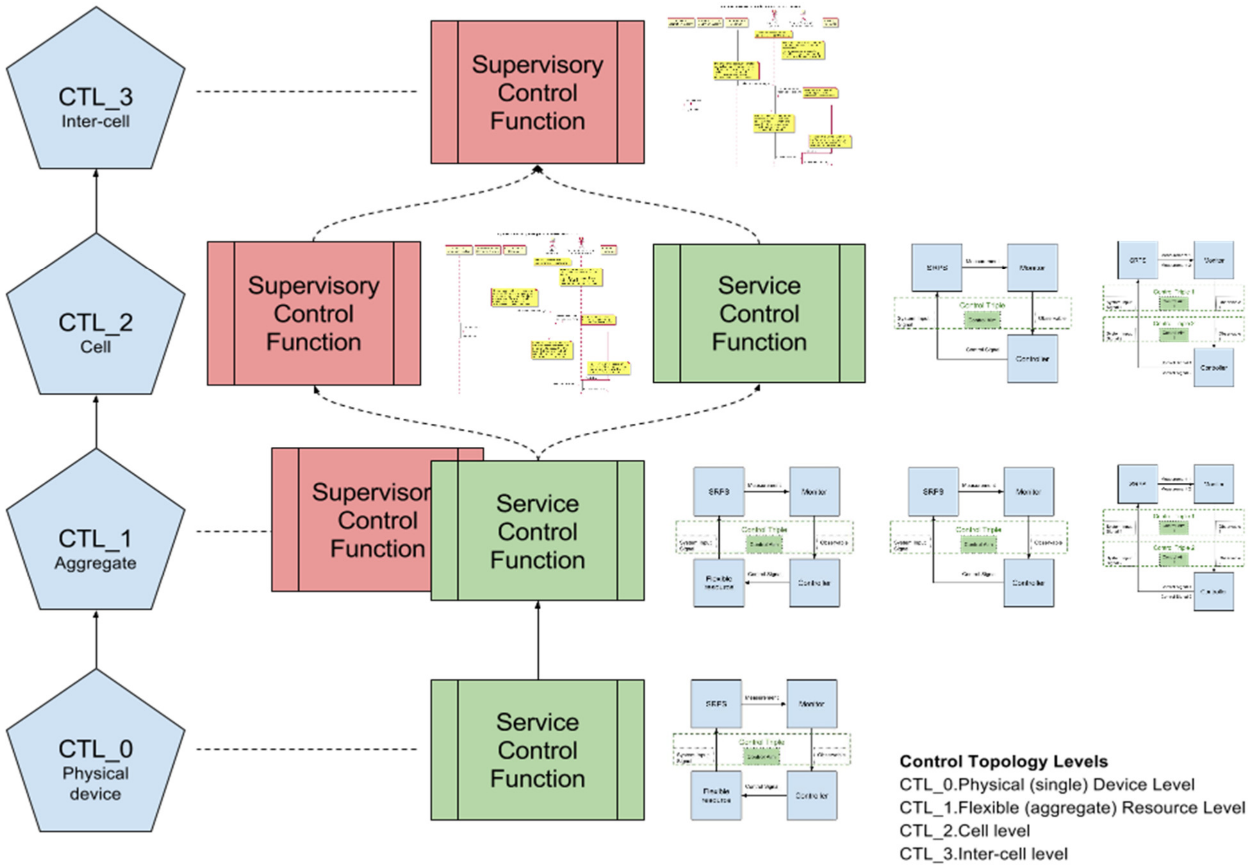

Figure 12 - Representation of Supervisory Control functions in Time Sequence Diagrams (TSD), and Service Control functions in Control Loop Diagrams (CLD), depicted per Control Topology Level (CTL).

In the next paragraphs, trial architectural options are worked out.
These are still to be further diversified according to the stepwise procedure described in the previous paragraph 7.1. Stepwise procedure for architectural control options.

4.3 Top level Control Function- Use Case Inertia Response Power Control

The main objective of inertia response power control - IRPC (B1.IRPC) is to minimize stationary frequency fluctuations at cell level or within the synchronously connected power system. The desired objective is achieved by different control topology levels, at CTL3 based on the capability of each cell, the inertia reserve contribution from each cell is defined. At CTL2, a sequence of interactions and negotiations between the different actors is defined (i.e. cell operator, market agent, resource owner). At CTL1 a sequence of interactions between cell operators and aggregated units is defined and finally at CTL0 an interaction between the device and the grid is defined.

Different variants could play a role in achieving the desired objective, for example the resource efficiency, availability of observables, control structure, control strategy and possibility of sharing resources across cells. In the ELECTRA context it has been assumed that the grid is for 2030+ which allow us to assume the availability of different measures and observables which could be not present today. In the following we assume two main cases, static scheme and dynamic scheme. In the static control the preplanned inertia value

Static control:

Since the frequency is a global parameter of the power system, the inertia reserves should be coordinated at synchronous area level. Different variants will have a fundamental role in this scheme. First of all due to the high integration of inverter based generation replacing rotating machines over the day result in insufficient physical inertia in the system which could be compensated by virtual inertia (from energy storage system or wind turbine with inertia emulation). The cell operator has to choose the resources participating in the inertia control based on different parameters (e.g. prices). Moreover, different control structures could be applied (i.e. centralized, decentralized and distributed) and need to be defined a priori. An example is presented in next table.

Centralized	The devices set points are calculated centrally in the control room
Decentralized	The devices set points are calculated locally at each device based on local measures
Distributed	The devices set point are calculated based on distributed algorithm over the participating units and the different measured points

The controller topology also could differ from one situation to another, for example a proportional controller or a fuzzy controller. In the next table the different variants which could influence the top level control function are presented.

Aspect of Variation	Options
Control Error	df/dt, Δf
Control structure	Centralized, Decentralized, Distributed
Control strategy	Proportional, Fuzzy
Resources	Cell level, inter cell level

In the following we assume the inertia reserves are coordinated at synchronous area level (CTL3). In the WoC concept, cell operator is responsible of his own cell and consequently need to ensure certain level of inertia (i.e. physical inertia as well as virtual inertia) coordinated at a synchronized area level as shown in Figure 13 (CTL2).

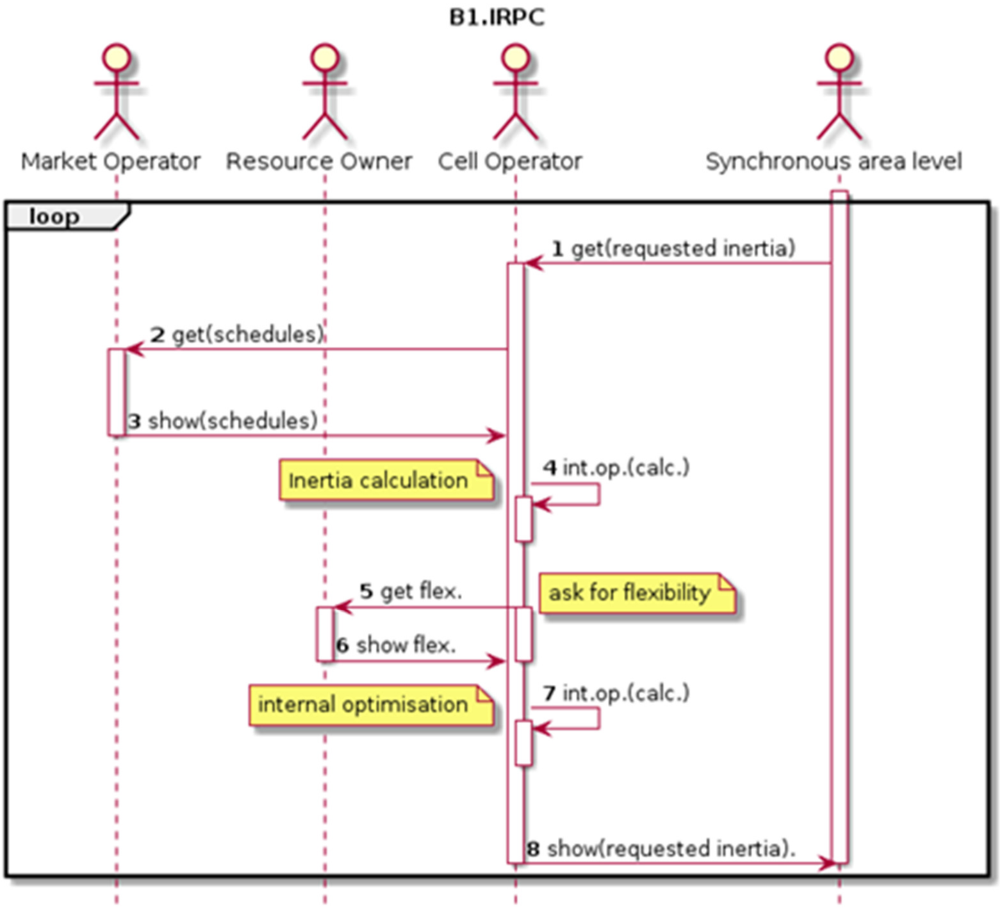

Figure 13 - Time sequence of interactions among actors to inertia value at each cell within the synchronised area.

The objective of this supervisory control is to identify the inertia set points for each cell after coordination on a synchronized level as following: Step1 the cell operator gets informed about the requested set point, steps 2-4 describe data reported by the market operator and elaborated by the cell operator. Steps 5-7 describe negotiation between aggregator and cell operator and finally confirmation of the requested set-point. Practically the cell operator receives the inertia set point coordinated on the synchronous area level afterwards inform the market about his own surplus of inertia which could be delivered to other operators. Based on this information (also from other cells and aggregators) the market agent sends the schedule to the cell operator. The cell operator elaborates all the data and asks the resource owner (aggregator) for availability of a certain set point.

The above described procedures aim to organize and coordinate at synchronize area level the IRPC control service parameters in order for a cell to be able to minimize the frequency fluctuation. In figure 14 the control actions are described which constitute the actual process of IRPC after incidents that disturb the power system (on a cell or web-of-cells level) (CTL1). As shown in figure 14 the voltage is measured on the SRPS level (e.g. certain bus-bar). The monitoring block utilizes an algorithm in order to calculate the frequency to be delivered to the controller. The controller calculates the df/dt and set the resources set points based on a droop control. The device output will be an active power deviation proportional to the frequency fluctuation.

The control loop is presented in figure 14

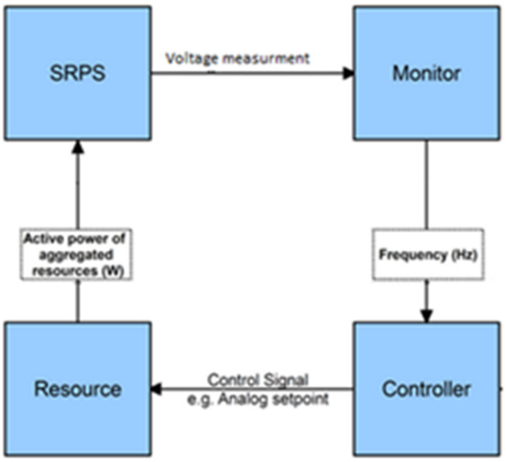

Figure 14 - CTL1

For the CTL0 the description is the same as in CTL1 but acting on each single device instead of aggregated resources as shown in figure 15.

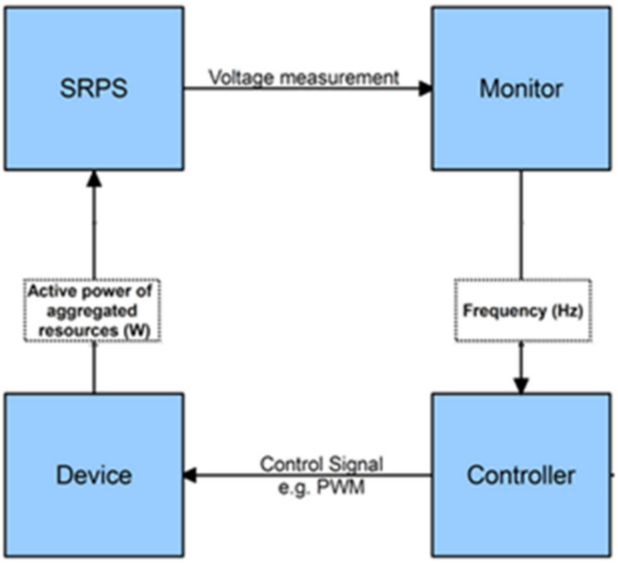

Figure 15 - CTL0

Reserve Volume Definition System

The control objective of the controller is the definition of the required procurement capacity for each cell. The capacity to procure for each cell is a fixed value over time and defined at synchronized area level for the day ahead.

Observables or measurements needed are defined based on the controller algorithm and characteristics for each cell.

The output signal of the controller is the reserve set-point, which will be translated into active power to be fed into the grid.

Timing of the controller: Reserves have to be procured for the day ahead (in this case we assume the reserves are constant for example non weather dependent).

Dynamic control:

Assuming the high integration of renewable energy (weather dependent) and electric vehicles (not always connected to the grid) the system inertia will be variable over the time. The cell operator is responsible of verifying the availability of the predetermined inertia on the synchronous area level. As mentioned before different variables will have a role in the control. Assuming the virtual inertia is delivered from electrical vehicles (energy storage system), the operator will have a validation process each 15 minutes to guaranty the inertia value and probably to negotiate reserves with other resources owner. The resource owner has his own algorithm to verify the resources availability. The time sequence diagram is presented in figure 15 (CTL2).

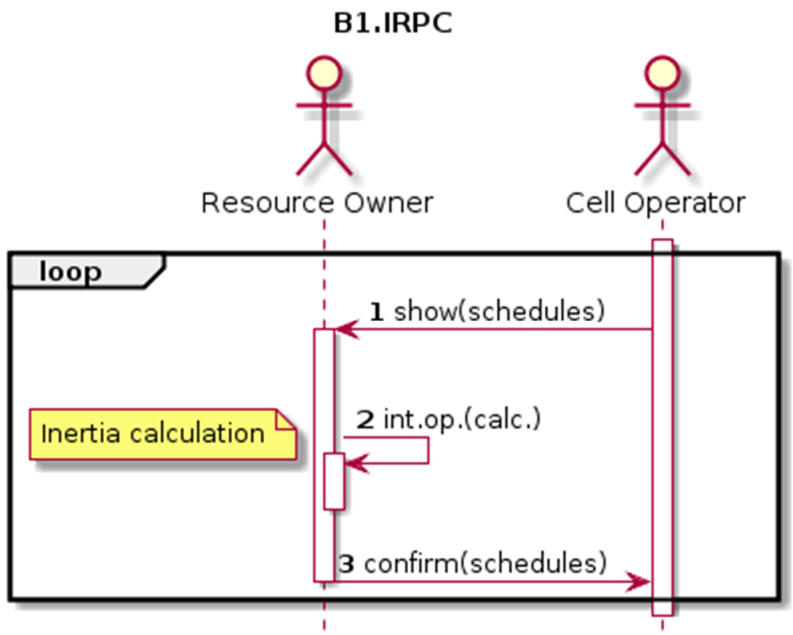

Figure 16 - Sequence of interaction among cell operator and resource owner.

The CTL1 and CTL0 are exactly the same as in the static case presented in Figure 15 and Figure 16.

Reserve Volume Definition System

The control objective of the controller is the definition of the required procurement capacity for each cell. The capacity to procure for each cell is a fixed value over time and defined at synchronized area level for the day ahead. In contrast with the static case, the capacity to procure from each resource owner should be defined each 15 minutes.

Observables or measurements needed are defined based on the controller algorithm and characteristics for each cell.

The output signal of the controller is a reserve set-point each 15 minutes that the cell system operator has to procure within his cell.

Timing of the controller: Reserves have to be procured on a 15-minute time-step since many market mechanisms operate on a 15-minute time-step.

4.4 Top level Control Function- Use Case Frequency Containment Control

The basic objective of frequency containment control - FCC (B2.FCC) at CTL3 is the identification and regulation of a characteristic steady-state response of power to frequency deviations at the Synchronous Area level. To this end, the UC described by the sequence diagram in figure 1 is implemented. In a nutshell, the objective of this supervisory control procedure is to identify the operating conditions of the whole area, namely scheduled (main peak) production/consumption, to calculate the response requirement during an incident, namely with how much power the FCC reserves of the synchronous area will contribute to an imbalance and, finally, based on the capability (energy yield) of each cell, the process calculates the reference contribution of each cell, thereby defining a set point for each cell operation at CTL2.

These three steps are specified in the sequence diagram of Figure 17 in the following way: Steps 1-3 describe data retrieving from the market operator (agent) who is aware of the Day-Ahead/Intra-Day schedules. These data are used at step 3 for the calculation of the network power frequency characteristic (NPFC) value (λu) at the synchronous area level. This value constitutes the NPFC setpoint for the whole synchronous area. Following this calculation, the λu controller requests the energy production of each cell from the block that is responsible for observing these values at the relevant steps 4-7. After the λu controller has acquired the information from Ei observer it calculates and dispatches the final contribution by each cell in the steps 8 and 9. This contribution is represented by the value λi, which is the NPFC setpoint for each cell.

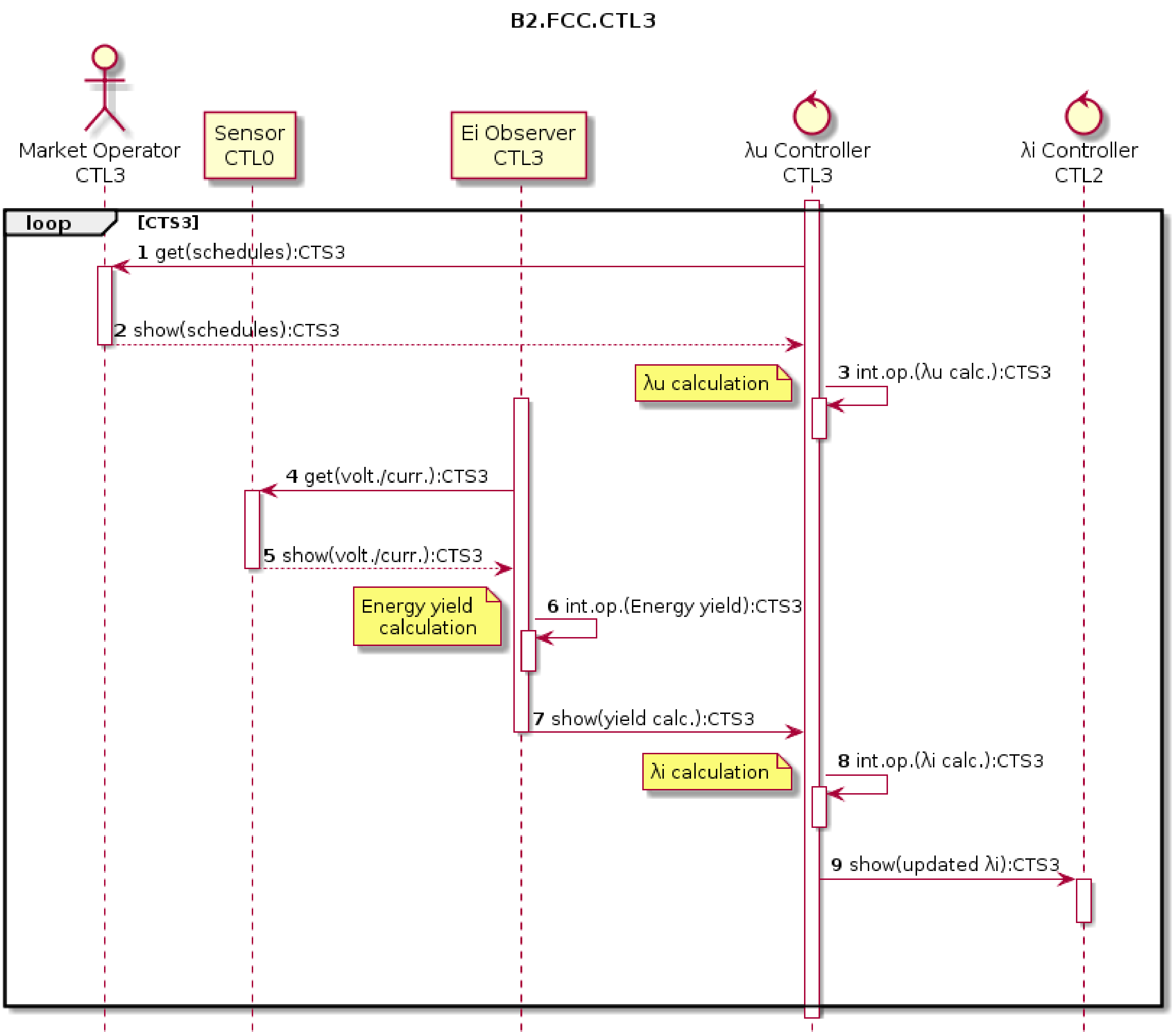

Figure 17 - Sequence of interactions among actors to ensure NPFC (or λu) within a Synchronous Area or any other web-of-cells area

The procedure that is followed at CTL2 of FCC is divided into two main scenarios, namely the assignment of reserves prior to the regulation or activation stage of FCC and the regulation of the characteristic within a cell according to the requirement of the Synchronous Area operation.

The process of flexibility procurement/assignment is depicted Figure 18. In this diagram, the process is shown the simplest possible form involving only the two main actors, namely Resource Owner and Cell Operator. This representation makes the flexibility assignment independent of the mechanism used in each UC variant. This way, not only does the description cover a market procedure in general but also the possibility of having bilateral contracts between the parties and/or regulatory regimes that impose the provision of flexibility for FCC needs to specific resources. In any case, the resource owners submit their flexibility/availability to the cell operator (step 1), the cell operator thereafter calculates the dispatching schedule of the resources (step 2) and, finally this schedule is assigned to the individual resources (step 3).

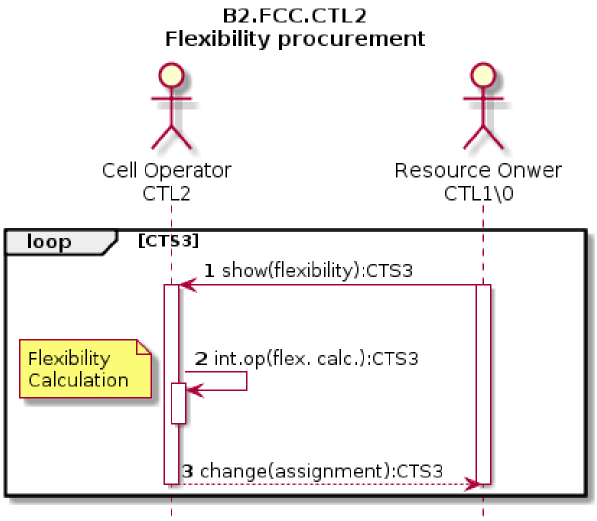

Figure 18 - Sequence diagram describing the process for flexibility procurement and assignment for FCC (CTL2)

Once the availability of resources is ensured by the previous process, the supervisory control can implement these resources to regulate the NPFC of the cell based on the λi setpoint identified by the CTL3 procedure. In this respect, the control process has to first identify the actual state of the cell in terms of power/frequency response. The procedure, as shown in Figure 19, starts with the exchange of information between the block that observes λi and the sensing devices (steps 4-6). After implementing the calculation algorithm, λi Observer communicates the information to the λi Controller block. The latter implements an internal operation (step 8) with the aim to identify the corrective actions in terms of parameters calculation that, thereafter have to be dispatched to resources/devices (more precisely to their FCC Controllers at CTL1/0), thereby correcting any observed deviations from the reference value. The last stage in the procedure described by steps 10-12 involves the update of the λi reference value by means of the interaction of the λu and λi controllers (CTL3 and CTL2).

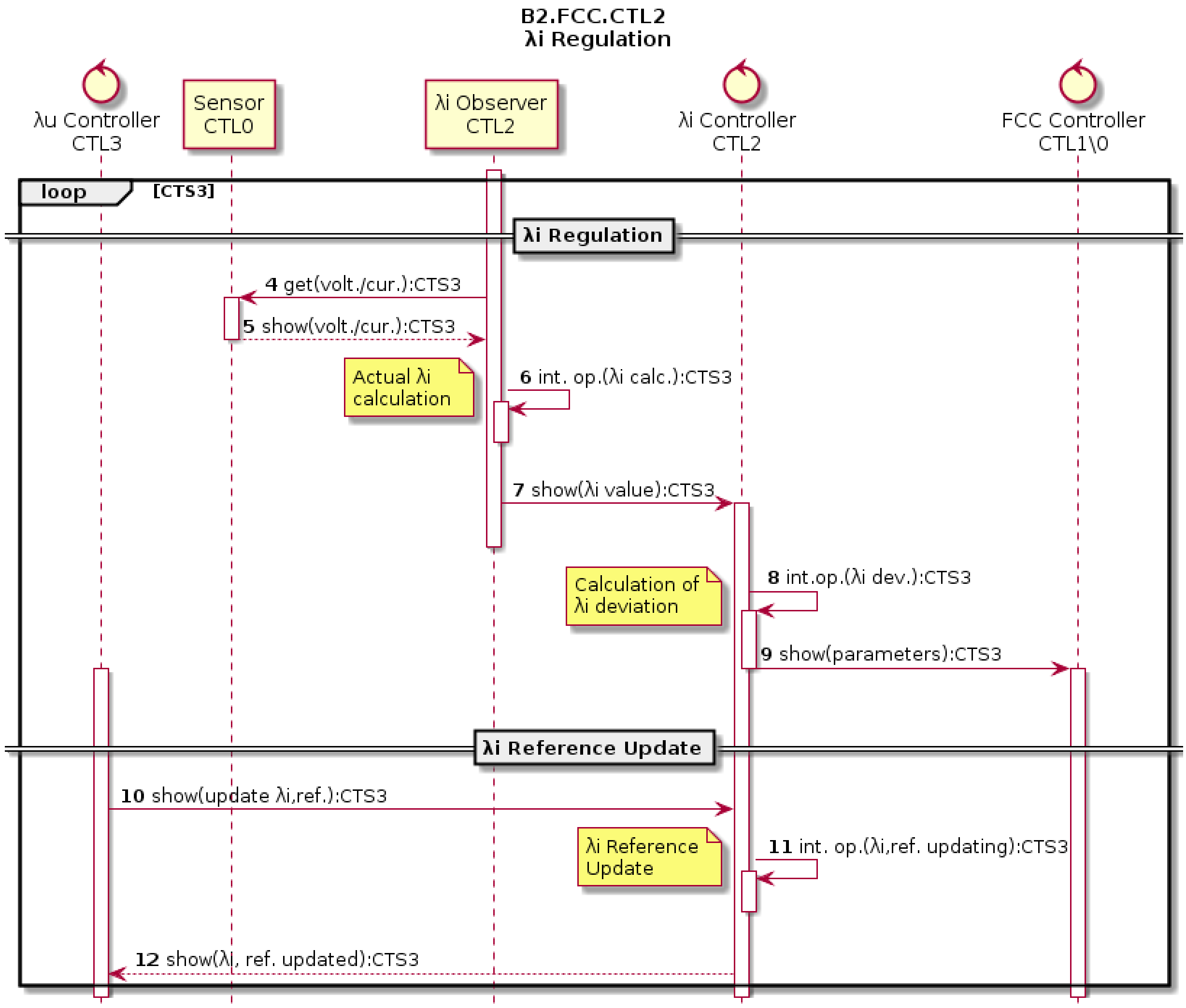

Figure 19 - Sequence diagram describing the process of λi regulation for FCC at CTL2

Last but not least, FCC involves service control procedures at resource (CTL1) and device (CTL0) levels. In contrast with the above described procedures that aim to organise the FCC control service parameters in order for a cell to be able to cope with an imbalance, the service control actions at CTL1/0 constitute the actual implementation of FCC under incidents that disturb cells' (and web-of-cells') balance. Both CTL1 and CTL0 schemes are similar in their concept and implementation. Thus, as shown in Figure 20 and 21 the operation is based on voltage measurement at the Point of Common Coupling for both the device and resource. The monitoring block utilises an algorithm in order to calculate the frequency with a satisfactory accuracy for the CTS of FCC resolution. The output is fed to the controller block, which compares the actual frequency with the reference value, thereby changing the output to satisfy the control strategy. For instance, if a droop controller is implemented, the output will be an active power deviation proportional to the frequency deviation. The active power signal is translated into a control signal that drives the device/resource according to the underlying technology of the latter. Finally, all devices/resources supply the system with an aggregated active power (deviation) to compensate the imbalance that causes frequency deviation.

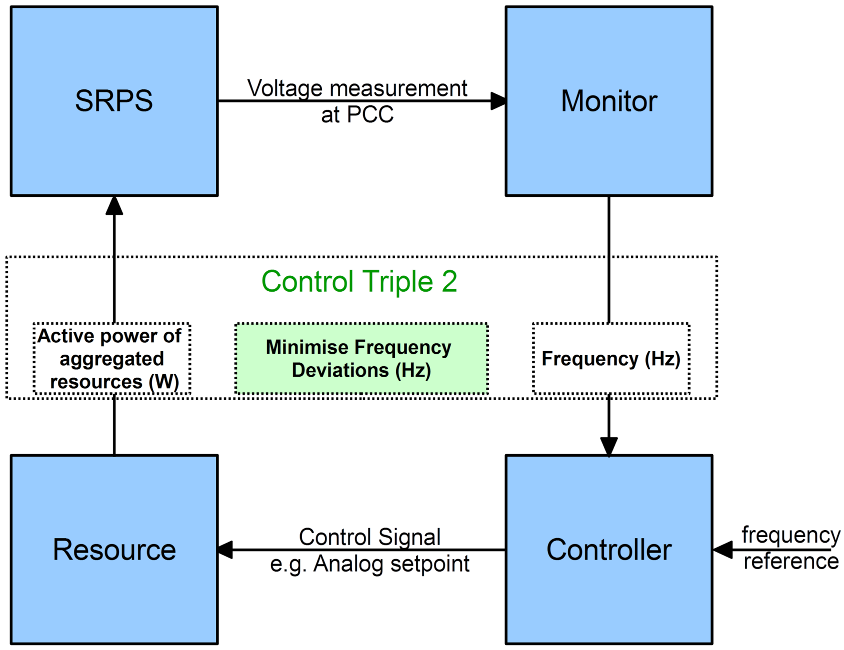

Figure 20 - Control loop for FCC service control at resource level (CTL1)

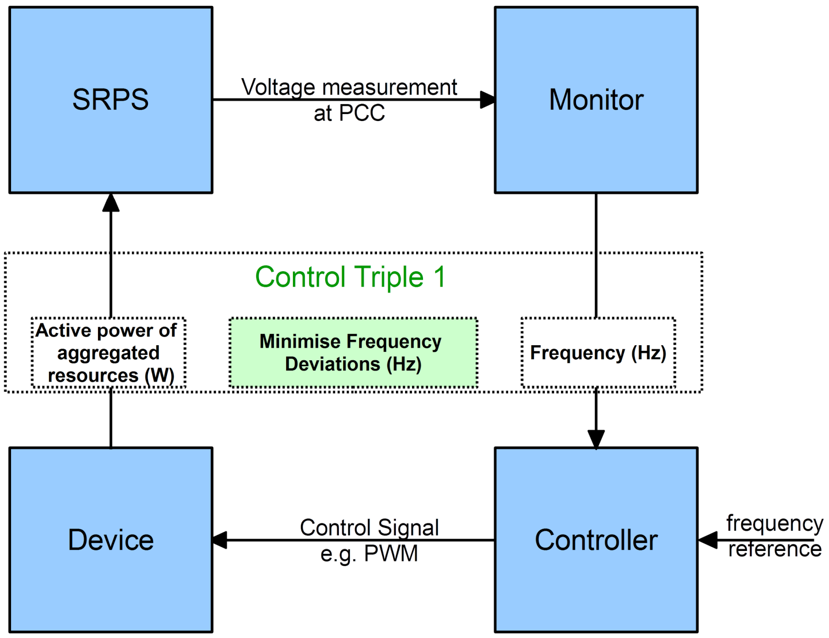

Figure 21 - Control loop for FCC service control at device level (CTL0)

4.5 Top level Control Function- Use Case Balance Restoration Control

An imbalance in the planned/predicted load versus production values within a cell causes changes in the power flows across cell borders. The objective of balance restoration control - BRC (B3.BRC) is to **restore the cell balance** and by doing so, restoring inter-cell load flows to their setpoint (secure) values, and consequently, restoring system frequency to its nominal value.

Based on the difference between scheduled power flow and measured power flow across the cell borders, available BRC reserves within the cell are activated. In traditional frequency restoration control, the restoration reserves providers are mainly large synchronous generators. Because of the decreasing availability of these large generators, different resources with flexibility, such as storage systems, curtailable and/or shiftable load, renewable energy resources, etc., are needed to be activated as balance restoration reserves in order to have sufficient reserve capacity available within a cell. It is also necessary that balance restoration reserve capacity can be procured in an economically optimum manner.

The balance of a cell is measured through comparing the scheduled power flows across the cell borders with the measured cell border power flows. In addition to this, power flows resulting from Frequency Containment Control actions are taken into account when calculating the cell imbalance. The amount of balance restoration capacity to activate is determined through a PI-controller with the cell imbalance as input.

Balance Restoration reserves are procured within a cell and ordered in a merit order, based on the costs for reservation as well as the physical state of the network. The physical state of the network is taken into account to avoid that the activation of certain reserves introduces congestions in the network.

When a cell imbalance occurs, the required reserves are activated according to the merit order. Reserves are activated for a maximum period of time; Balance Steering Control takes over the balance restoration reserves after this maximum activation time.

Aggregators, which aggregate the flexibility from a portfolio of many (different) resources, can act as a restoration reserve provider. In order to comply with a reserve activation request, the aggregators must ensure that the required reserves are activated within the agreed ramp-up time. Therefore, each aggregator has to be aware of the overall flexibility of its combined portfolio, and thus needs to know the availability and state of the resources within its portfolio. Resources for restoration reserves are flexible resources in its broadest interpretation: synchronous generators, renewable resources, curtailable load, shiftable load, electricity storage, etc.

The overall control process of BRC consists of 2 phases: *procurement phase*, and *real-time control* phase.
One variant of the procurement phase has been worked out, depicted in Figure 22. Two variants of the real-time control phase are worked out, depicted in Figures 23 and 24.

The **overall control aim** of the procurement phase is the procurement of an adequate amount of Balance Restoration Reserves at minimum cost.

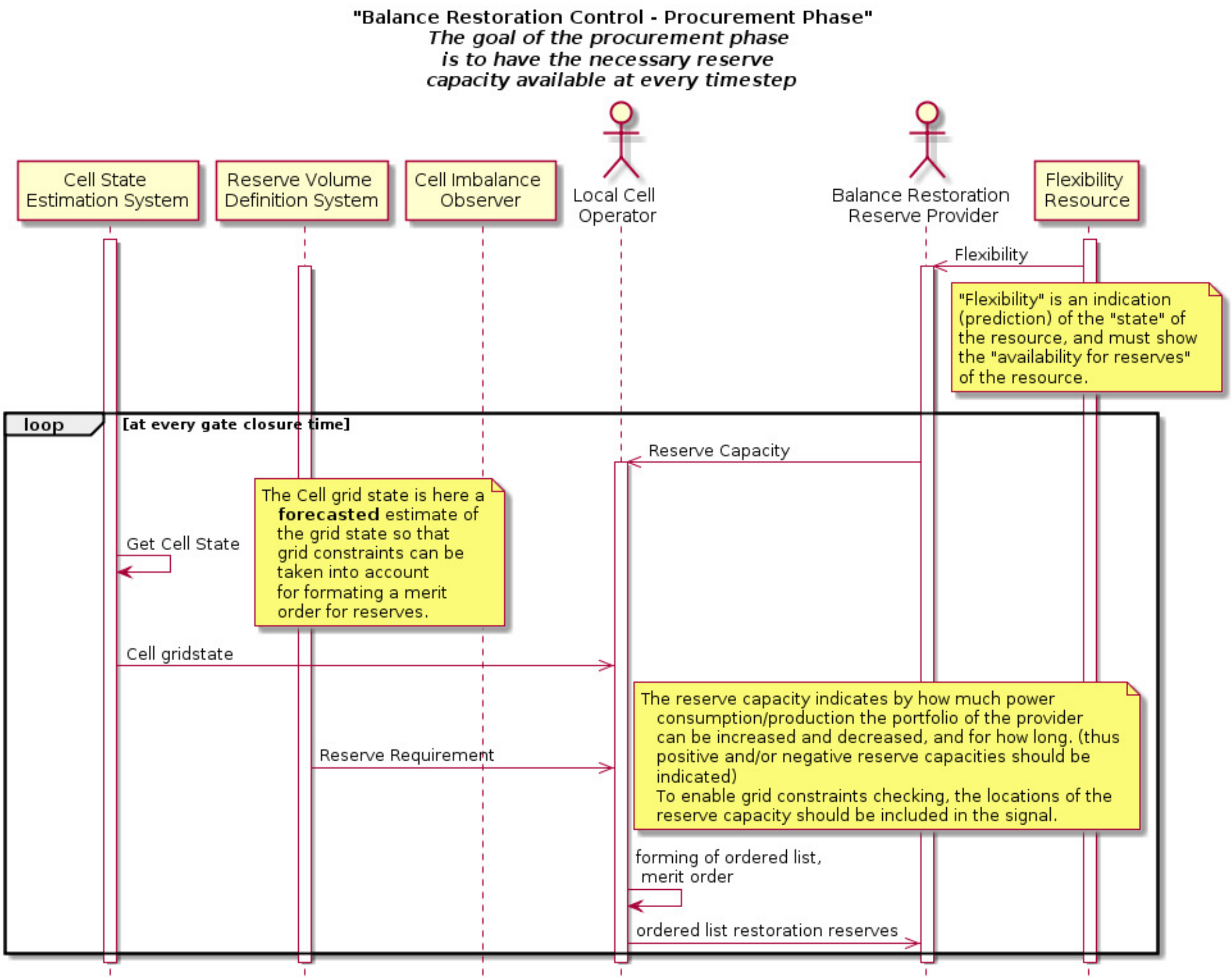

Figure 22

Reserve Volume Definition System

The control objective of the controller is the definition of the required procurement capacity for each cell. The capacity to procure should be defined for each future timestep. The procurement capacity can be a fixed value over time, but depending on the cell characteristics can be a changing value over time.

Observables or measurements needed for this controller are the characteristics of the cell that enable the calculation of a BRC procurement capacity: probability of imbalance incident, size and timing of imbalance incidents, amount of FCC reserves, etc.

The output signal of the controller is a reserve capacity, per timestep, that the cell system operator has to procure within his cell.

Timing of the controller: Reserves have to be procured per timestep. Since many market mechanisms operate on a 15-minute timestep, it would be logical to follow a 15-minute timestep base for reserve procurement. To allow the cell system operator the time to procure the required capacity, the controller output signal should be available quite some time before T0 (e.g. 1 hour before).

Local Cell Operator

The control objective of the controller is the setting up of a so-called ‘merit-order’ of the procured reserves. The merit order indicates which reserves will be activated at a certain measured imbalance. The merit order is set up based on costs of the reserves. The cell system state (or a

prediction of the cell system state) can also be taken into account so that the activation of reserves does not induce grid congestion issues.
Observables or inputs for this controller are the cell system state, and the reserve capacity bids of every restoration reserve provider willing to bid within the cell. The required capacity to procure, is also an input for this controller.
The output of the controller is a merit order that at least contains the required restoration reserve capacity, at minimal cost. The reserve capacity providers receive a signal to let them know whether or not they are included in the merit order.
Timing of the controller: The merit order should be available at least 15 minutes before possible activation time (T0).

Balance Restoration Reserve Provider
The control objective of the controller is the definition of reserve capacity bids based on the portfolio of the reserve resources of the restoration reserve provider. Reserve capacity bids indicate how much reserves can be offered, at what time step, and at what cost.
Observables or inputs for this controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.
The output of the controller is a restoration capacity bid, which indicates how much reserves can be offered, at what time step, and at what cost.
Timing of the controller: The capacity bids should be available at least 1 hour before possible activation time (T0), to allow the system operator enough time to set up the reserve merit order.

Flexible Resource
The control objective of the controller is the definition of the flexibility state of the flexible resource. This flexibility state must indicate what the options are for the resource to be controlled so that inherent resource-constraints are not violated.
Observables or inputs for this controller are dependent on the resource.
The output of the controller is an indication of the flexibility state of the flexible resource.
Timing of the controller: The flexibility state information should at least be available 1 hour before possible activation.

The **overall control aim** of the real-time control is the activation of an adequate amount of Balance Restoration Reserves at minimum cost, without violating any grid constraints. The required reserve capacity should be activated within a timescale of 15 minutes.

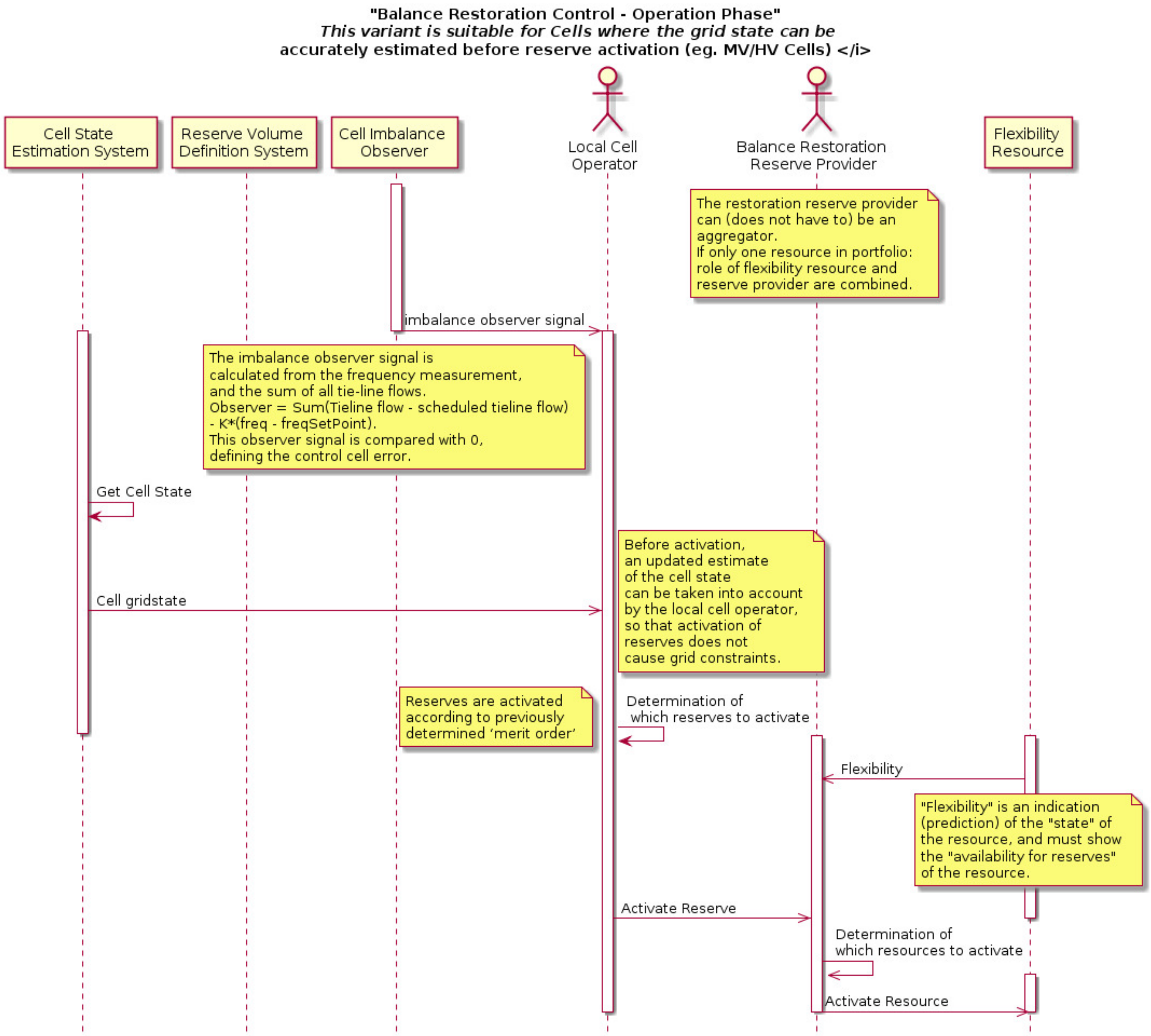

Figure 23

Local Cell Operator

The control objective of the controller is the provision of a reserve activation signal for each of the restoration reserve providers, based on the previously defined merit order and based on the measured imbalance in the cell. To avoid grid congestion issues, the (updated) cell system state information can be taken into account when defining the reserve activation signals.

The amount of reserves to activate is defined through a PI-controller, with the cell imbalance as input signal.

The observable or input for this controller is the cell imbalance. The cell imbalance is defined as the difference between scheduled tie-line flows and measured tie-line flows, corrected with the FCC contribution of the cell resources (indicated in the Figure as K*Δf).

A second input is the cell system state information which can be taken into account when determining which reserve should be activated, to avoid grid congestion issues.

The output of the controller is a restoration activation signal for each restoration reserve provider: the activation signal should contain how much reserves should be activated and for how long.

Timing of the controller: The reserve activation signals should be present in the order of minutes after an imbalance occurs.

Balance Restoration Reserve Provider

The control objective of the controller is the activation of the required capacity taking into account the state of the flexible resources within the portfolio. After a predefined ramp-up time, the required capacity should be activated by sending the necessary activation signals to certain resources within the provider's portfolio.

Observables or inputs for this controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.

The output of the controller is an activation signal to each (or a selection) of the resources within the portfolio.

Timing of the controller: activation of the reserve capacity should be at least within 15 minutes after an imbalance was detected. Therefore, the timing of the controller should be that the necessary activation signals are determined and sent within a timescale of a couple of minutes.

Flexible Resource

The control objective of the controller is the adequate response to a resource activation signal.

Observables or inputs for this controller are dependent on the resource.

The output of the controller is a change of power exchange, dependent on the activation signal, with the cell system.

Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance has been detected. Therefore, the timing of the controller should be that the necessary power change is realized at least within 15 minutes from the imbalance detection. Ramp-up times of different resources may differ.

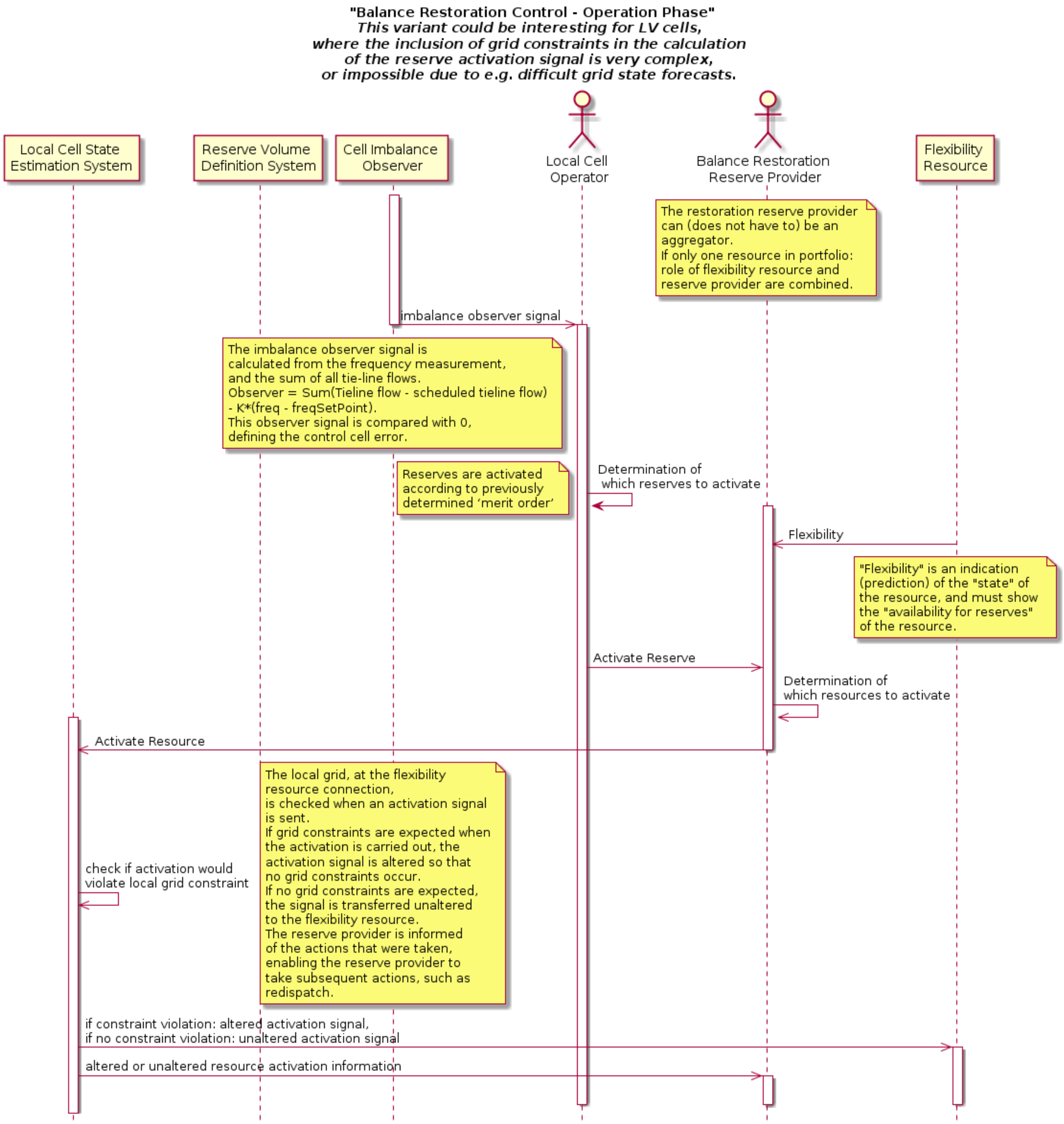

Figure 24

Variant 2 of the BRC real time control phase has been developed, because for some cell systems, such as for example LV-cells, a prediction of the grid state is very hard to obtain since too many parameters (such as renewable resource production, power consumption of small groups of consumers, etc.) have a very low predictability.

In that case, it is almost impossible to take a prediction of the cell system state into account when the merit order for reserves is determined. One possible option to prevent grid congestion issues during BRC, is to take grid prevention measures at the activation time of the resources.

Local Cell operator

The control objective of the controller is the provision of a reserve activation signal for each of the restoration reserve providers, based on the previously defined merit order and based on the measured imbalance in the cell. If a certain restoration reserve provider informs that because of grid congestion issues it cannot provide the necessary capacity, subsequent reserve providers are activated to eventually obtain the required restoration reserve.

The amount of reserves to activate is defined through a PI-controller, with the cell imbalance as input signal.

Observable or input for this controller is the cell imbalance. The cell imbalance is defined as the difference between scheduled tie-line flows and measured tie-line flows, corrected with the FCC contribution of the cell resources (indicated in the Figure as $K^*\Delta f$).

The output of the controller is a restoration activation signal for each restoration reserve provider: the activation signal should contain how much reserves should be activated and for how long.

Timing of the controller: The reserve activation signals should be present in the order of minutes after an imbalance occurs.

Balance Restoration Reserve Provider

The control objective of the controller is the activation of the required capacity taking account the state of the flexible resources within the portfolio. After a predefined ramp-up time, the required capacity should be activated by sending the necessary activation signals to certain resources within the provider's portfolio. If a certain resource is prevented from being activated due to grid congestion (see Flexible Resource controller below), the controller should redispatch the required activation capacity within it portfolio. If this is not possible, this should be communicated to the Cell Operator controller, so that other restoration reserve providers can be activated.

Observables or inputs for this controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.

The output of the controller is an activation signal to each (or a selection) of the resources within the portfolio.

Timing of the controller: activation of the reserve capacity should be at least within 15 minutes after an imbalance was detected. Therefore, the timing of the controller should be that the necessary activation signals are determined and sent within a timescale of a couple of minutes.

Flexible Resource

The control objective of the controller is the adequate response to a resource activation signal. When activation according to the required signal would cause grid congestion issues, based on the local grid state, the resource activation signal is altered to prevent grid congestion issues by a grid congestion prevention control. For example, if the local grid voltage at the connection point of the resource is relatively low, and the resource is required to consume more, the grid congestion prevention can alter the activation signal to prevent undervoltage issues.

Observables or inputs for this controller are dependent on the resource. An indication of the local grid state, e.g. a local voltage measurement, is required for the grid congestion prevention control.

The output of the controller is a change of power exchange, dependent on the activation signal, with the cell system. If grid congestion prevention has caused a difference in resource activation, this is reported to the cell operator and balance restoration reserve provider so that subsequent measures can be taken.

Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance was detected. Therefore, the timing of the controller should be that the necessary power change is realized at least within 15 minutes from the imbalance detection. Ramp-up times of different resources may differ.

4.6 Top level Control Function- Use Case Balance Steering Control

Supervisory control actions for balance steering control - BSC (B4.BSC) start at CTL3 (inter-cell level) with the scenario of procurement and assignment of flexibility for BSC. This process is defined at CTL3 because BSC can utilise resources not exclusively within the interested cell but also resources from adjoining cells. Thus, flexibility has to be identified within an area larger than one cell's area pools which may be identical to pools used by other market mechanisms. To this end, the procedure described in Figure 25 involves the participation of actors ranging from resource owners to market operator. More precisely, resource owners interact with BRPs (steps 1-3) in order to submit flexibility (the latter not exclusively for BSC service). The BRP is responsible for aggregating, assessing, assigning or rejecting flexibility offers. This action is followed by the notification of the resource owner as to the status of their offer. Thereafter, the BRP uses the flexibility to participate in the market process governed by a market operator. At this stage (step 4-6) schedules of the whole market area are determined. The following stage is the identification of the operating requirements for these specific schedules (steps 7-13). This is achieved by interactions between market and cell operators. The latter communicate their operating requirements to a Reserve Allocator, which is responsible for identifying the amount of flexibility to be used exclusively for the BSC service. This is achieved with the interaction between the reserve allocator and the BRP. Once the exact requirement is identified, the BRP updates schedules of resources so as to reserve the power capacity that is necessary for the BSC's needs. It is noteworthy that the actors shown in this scenario constitute roles rather than different entities, which means that in theory these roles could be assumed by a smaller number of actors. For instance, a party which is a cell operator could also assume the role of BRP or reserve allocator.

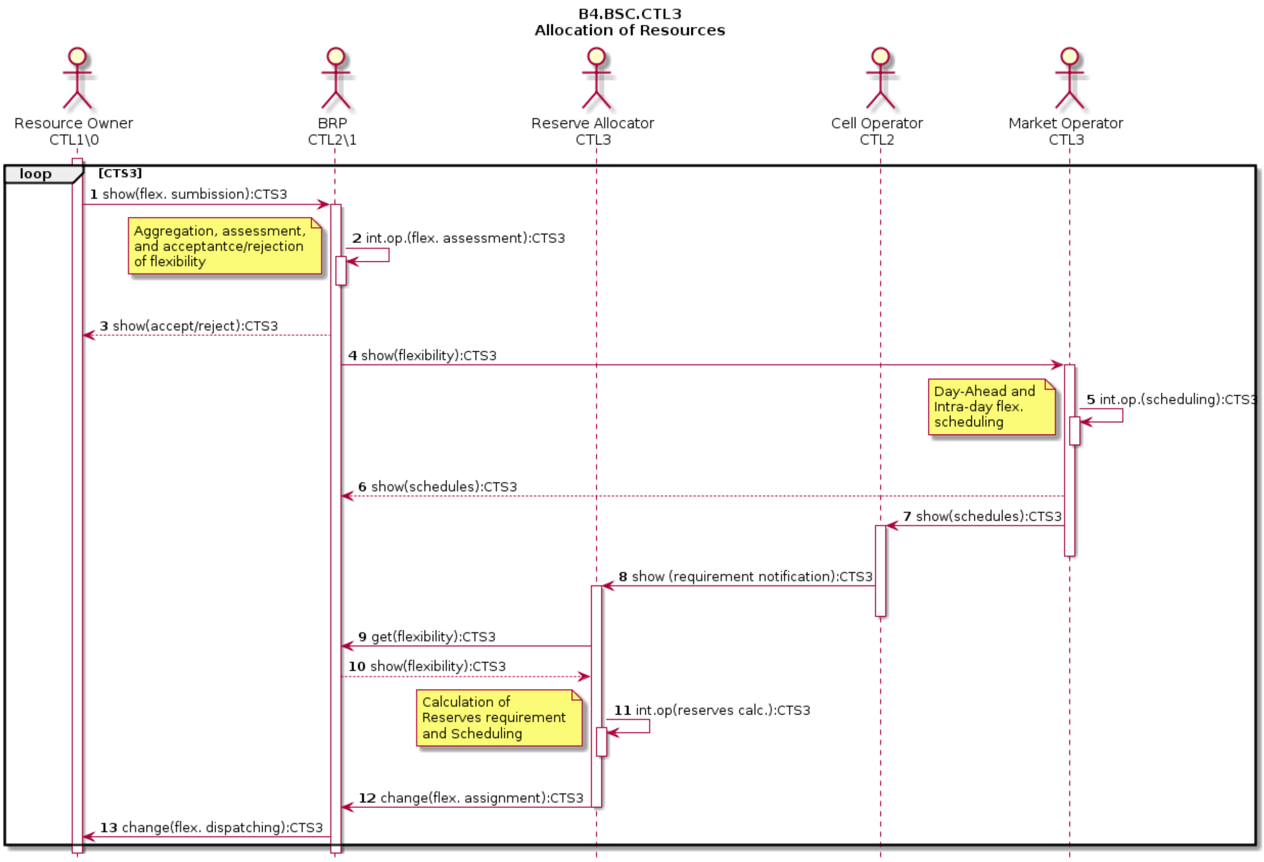

Figure 25 - Sequence diagram describing the process for flexibility procurement and assignment for BSC (CTL3)

The actions describing BSC at cell (CTL2) level are considered as supervisory control actions and, therefore, are described by the sequence diagrams in the following figures. More precisely, the operation of BSC comprises three scenarios, describing normal operation (Figure 26) proactive mode (Figure 27) and reactive mode (Figure 28). The normal operation scenario regards the state in which BSC is not activated by any kind of incident. This scenario involves two main stages. During the first stage (steps 1-3) BSC Controller interacts with the reserve allocator in order to obtain information about the reserve capacity of resources. The second stage of this normal operation scenario (steps 4-7) involves the interaction and function of forecasting so as to assess imminent imbalances. In order for the forecasting module to perform its task it has to retrieve data from the cell operator. These data are used by an internal process to forecast imminent imbalances. The resulted assessment is always communicated to the BSC.

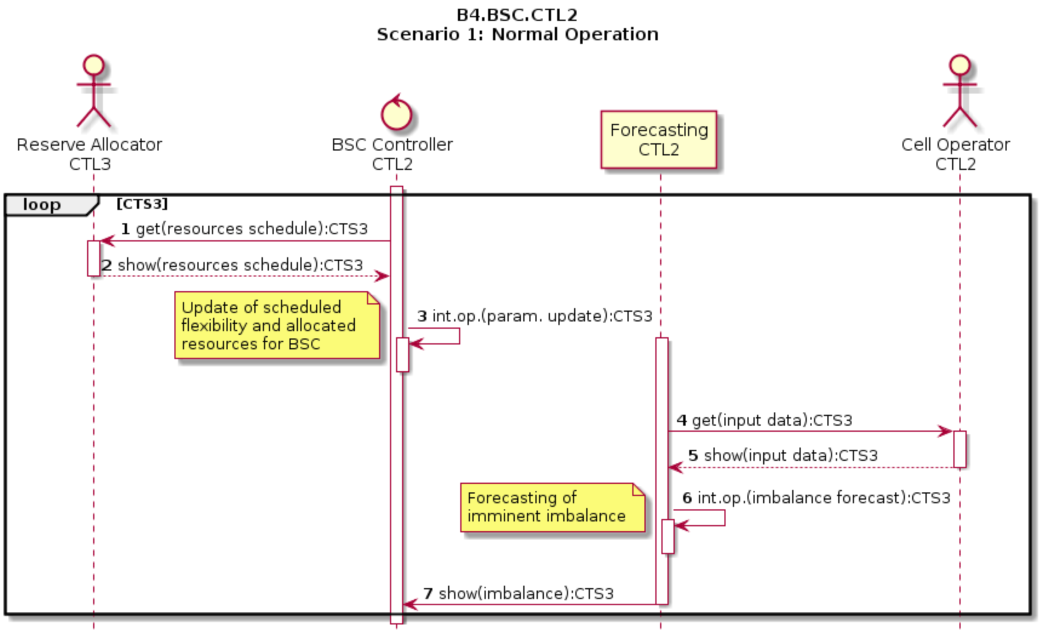

Figure 26 - Scenario referring to Normal Operation of BSC (CTL2)

What happens when forecasting detects an imminent imbalance is described in Figure 27. In this scenario, the proactive mode is described. More precisely, the first stage (steps 1-3) involves the BSC Controller's notification of the imminent imbalance by the forecasting. BSC then activates resources. The second stage of the process (steps 11-14) involves the observation of the aggregated power with the aim to fulfil the power setpoint determined by the forecast. To this end, the BSC interacts with the BSC power observation block which makes use of the Sensors data to obtain the required value. Thereafter, the third stage (steps 15-17) involves the efficiency calculation, based on the data acquired by the BSC power observer and its interaction with the Efficiency Observer. Once efficiency of the portfolio is obtained the information is communicated to the BSC Controller which, at the last stage, recalculates a power schedule and dispatches the values to the resources. The process is repeated for as long as this mode is activated.

Last but not least, the third scenario describes the operation of BSC at CTL2 as a result of the activation of BRC due to an incident (reactive mode). More precisely, as shown in Figure 28, the implementation of this scenario is identical to that in Figure 27 (proactive mode) with the difference that instead of the Forecasting block the actor that activates the process is the BRC controller which communicates the active power setpoint to the BSC controller. The latter follows exactly the same steps as with the activation by the Forecasting in proactive mode because fulfilment of the setpoint and maximisation of portfolio's efficiency are overarching objectives, regardless of the operating mode.

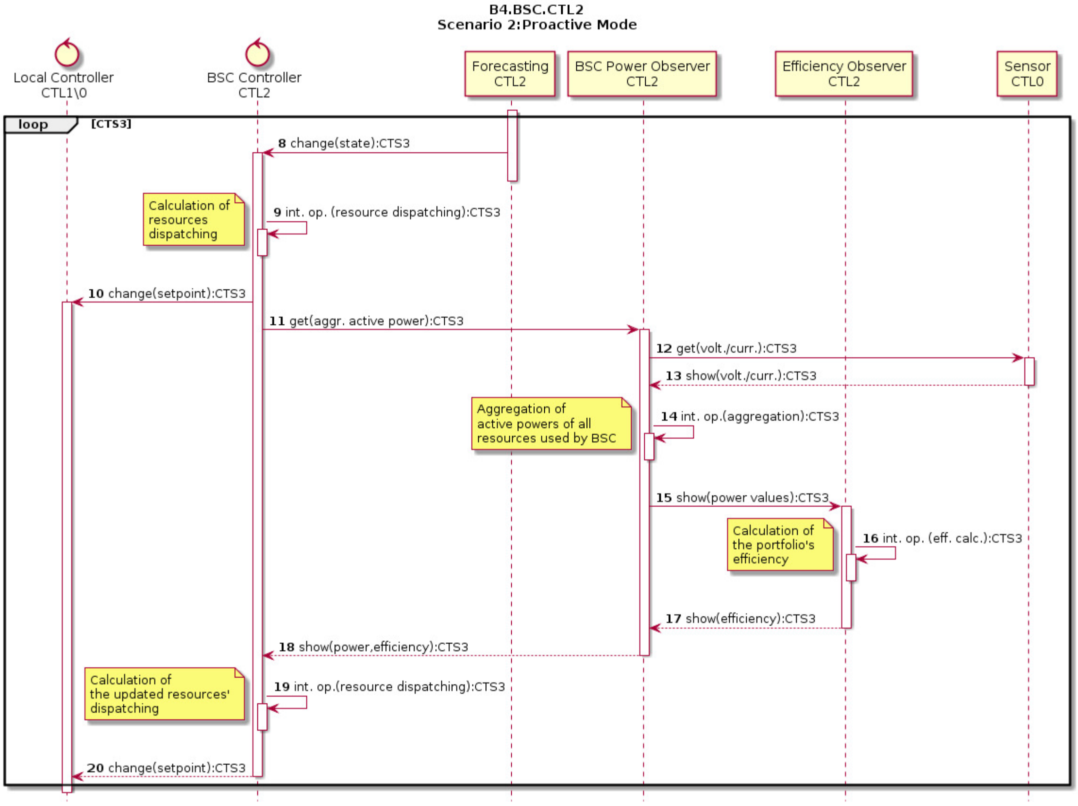

Figure 27 - Proactive mode of BSC (CTL2) as a result of an imbalance forecast

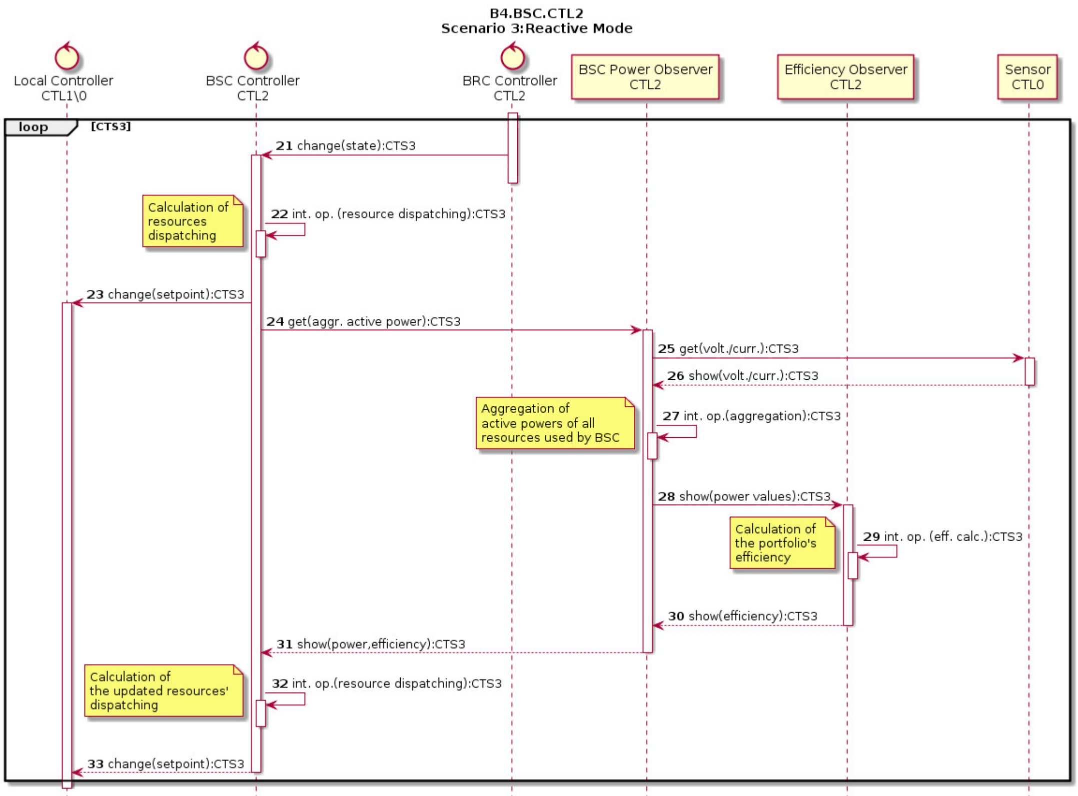

Figure 28 - Reactive mode of BSC (CTL2) as a result of BRC activation

4.7 Top level Control Function- Use Case Primary Voltage Control

According to the established terminology and control function division depicted in Figure 29, Primary Voltage Control - PVC (T1.PVC) is essentially a service control function operating either in CTL1 if the voltage control service is provided by aggregated flexibility resource, or in CTL0 if it is done by a single active/reactive power resource. Thus, on the contrary to other high level use cases, the principle of PVC operation can be explained mainly by means of control loop diagrams. Relevant description has been placed in "Annex: Technical description of Main Use Cases" in Chapter 6 "Technical description - Use Case T1.PVC".

Activation of a particular voltage control resource, as well as assuring the right amount of voltage control resources in a cell or in the vicinity of a particular node is a task of local cell operator within PPVC. However, operations like setting voltage reference value or changing controller parameters lie in the scope of PVC within the top control topology level for this use case, which is CTL2. The following time sequence diagram depicts these basic operations.

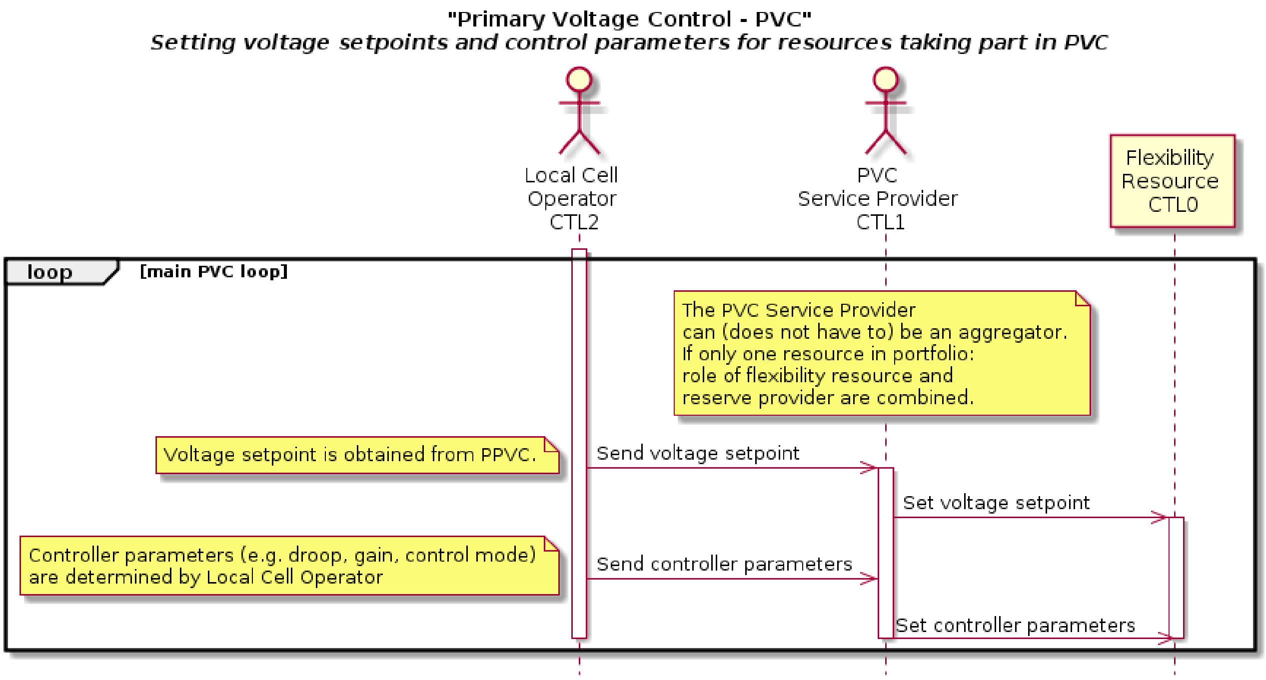

Figure 29

4.8 Top level Control Function- Use Case Post Primary Voltage Control

As starting point for the development of the use cases within the ELECTRA project the self-sufficiency of resources for voltage control procurement has been considered. This implies the control functions and the main relationships linking the operation of the different systems/actors/roles happen at a cell level (CTL2). The operation of the post-primary voltage control PPVC (T2.PPVC) is defined through the use of sequence diagrams describing two feasible scenarios:

1) Scenario 1: PPVC after PVC
2) Scenario 2: Proactive PPVC

4.8.1 PPVC after following PVC

The PPVC has been triggered as a result of a previous activation of the PVC. For this situation, the goal of the control is the restoration of the voltage values to those ones previous to the disturbance, optimizing the reactive power flows (and sometimes the active in LV grids) to minimize the losses.

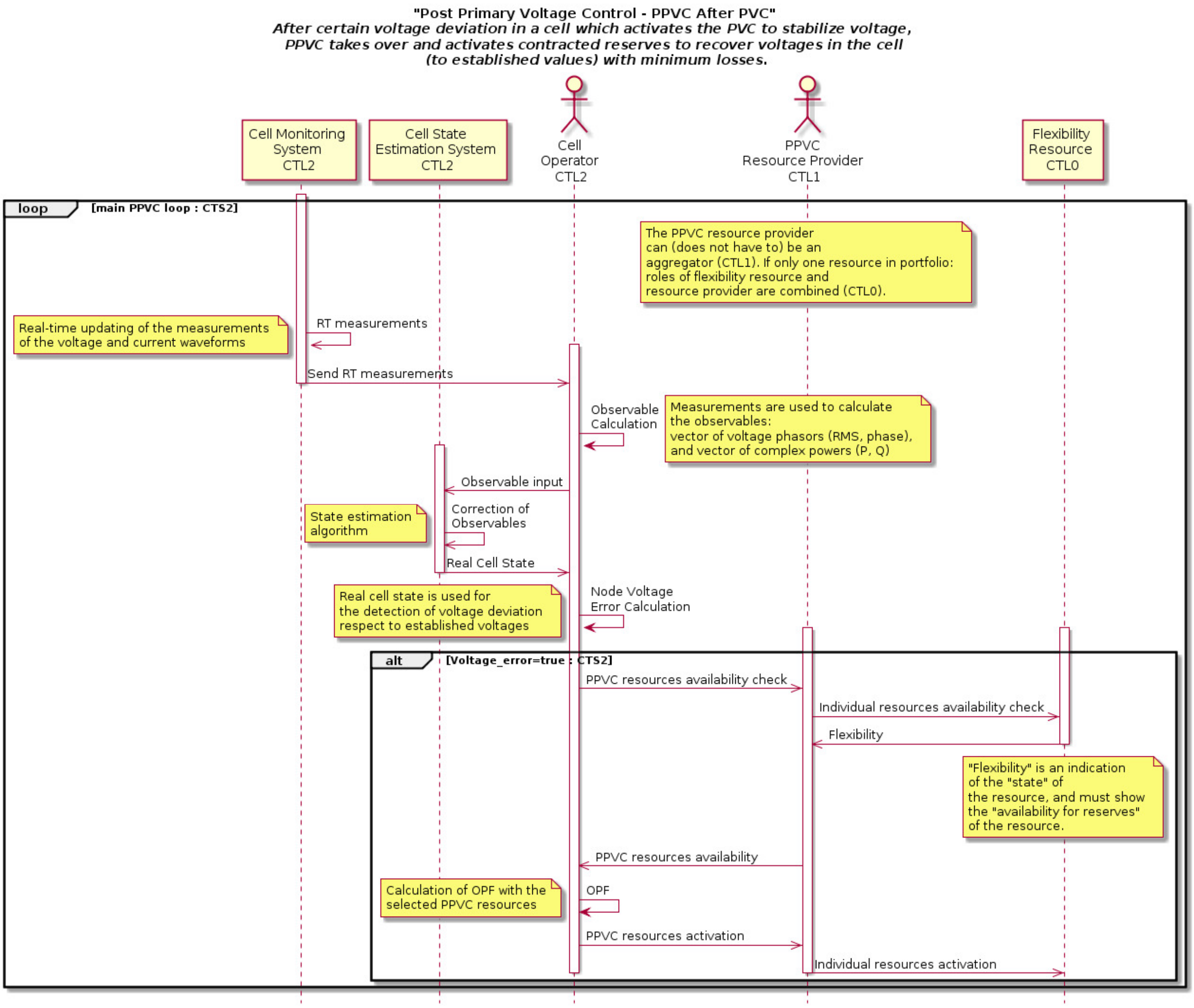

Figure 30 - Post Primary Voltage Control following activation of Primary Voltage Control

In Figure 30 is represented the first scenario by breaking down all the steps involved the process, as well as their corresponding CTLs and CTSs. The Cell Monitoring system is registering in real-time the voltage and current waveforms. Those measurements are sent to the cell operator, which calculates the observables from the data recorded by the cell monitoring system. Those observables, involved in the PPVC control loop, are the voltage phasors in the cell nodes (magnitude and angle), the complex power injected/consumed in the nodes and the power flows through the tie-lines. To compensate the associated error of the measurements and a potential unavailability of some measurements, the cell state estimation system launches a state algorithm is to evaluate the real state of the cell. The real cell state is the input for the Cell Operator to calculate the voltage error. If a voltage error in any cell node is detected, the Cell Operator activates the process for PPVC provision (inner control loop: CTS2). The PPVC provision is accomplished by the selection of the more cost-effective flexible resources, previously contracted in the PPVC market. In order to avoid availability problems, the cell operator checks the availability of the resources at the time needed. The flexibility resources in PPVC are those that had participated in the PVC but they have still room for selling extra flexibility in a dedicated PPVC market, such as converter-coupled sources, FACTS or controllable loads or those which are not fast enough for PVC so their operation is limited to the PPVC level. A PPVC availability check signal is sent from the cell operator to the PPVC resource provider. The PPVC resource provider (CTL1) can be an aggregator of several units of the portfolio but it also can be a resource big enough to participate in the market itself. If the PPVC resource does not sell its flexibility through an aggregator, the PPVC resource provider and the flexibility resource roles are combined (CTL0). If not, the aggregator must send another check signal downstream to the individual devices under its responsibility. After that, the flexibility resource sends back a flexibility signal to confirm its availability. Once the cell operator receives the information of available resources from the PPVC resource provider, it runs an optimal power flow (OPF) algorithm, verifying that no congestion problems are going to be produced and dispatching the different resources optimally. For the activation, the selected PPVC resources receive the activation signals from the PPVC resource provider. All the process corresponding to this first scenario must be executed in a CTS2 time frame.

4.8.2 Proactive PPVC anticipating PVC

The cell operator is comparing the foreseen voltage values in a 15 min horizon with the short-term forecast of the cell state and, by anticipating corrective actions (proactive operation mode), This operation mode reduces the number of PVC triggers that could happen as a consequence of bigger voltage deviations, becoming a cost-effective solution.

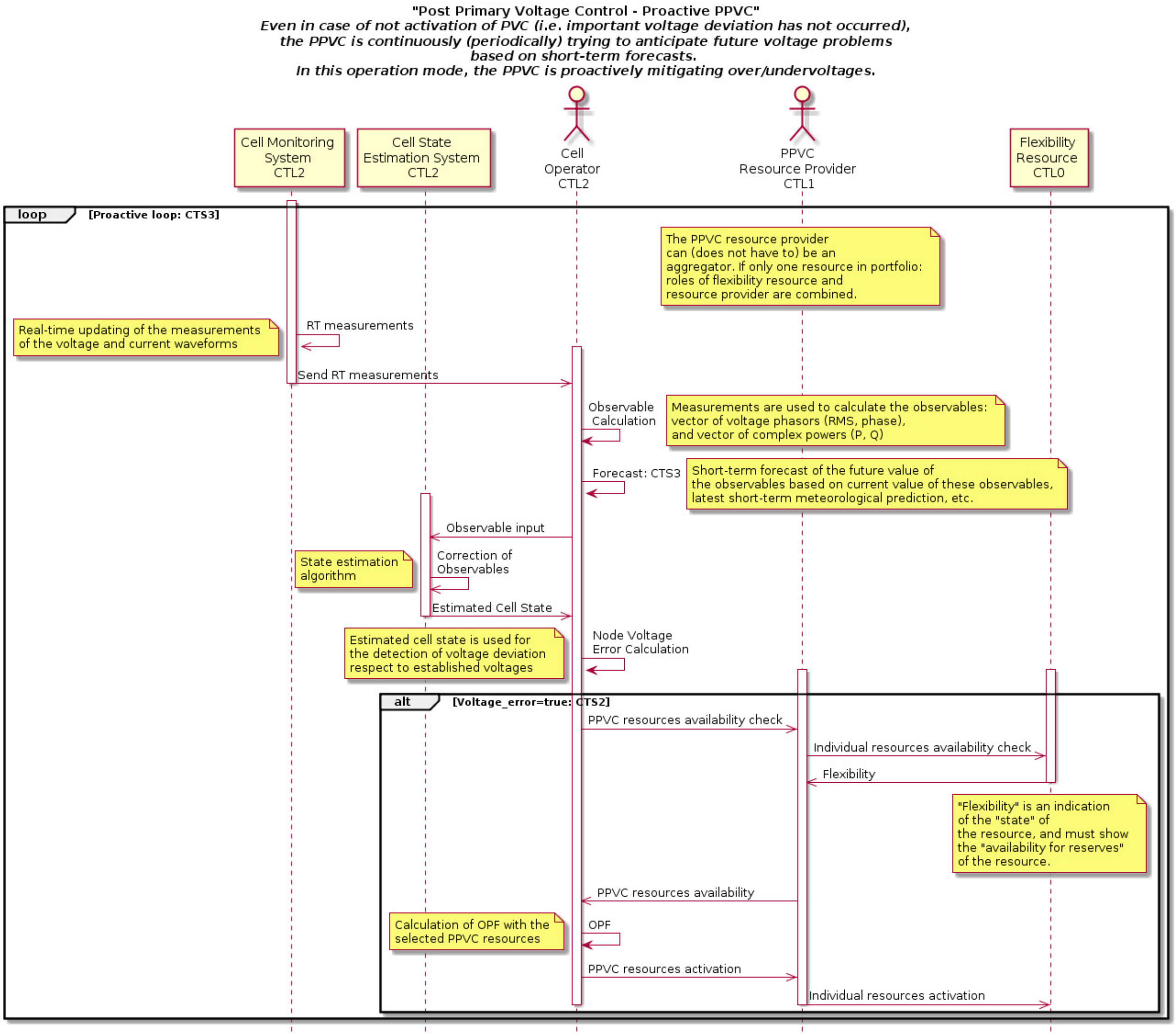

Figure 31 - Post Primary Voltage Control anticipating activation of Primary Voltage Control

In the second scenario, which sequence diagram is shown in Figure 31, the Cell Operator receives not only the measurements for the observables' calculation but also the information of the short-term forecast for the next 15 min. Even the cell monitoring system is going to be running continuously, some data, needed for the future observables calculation is only going to be received by the cell operator every 15 min (CTS3). This information is going to be bottleneck of the global execution time of the main PPVC loop. From the received data, the cell operator makes the short-term calculation of the future value of the observables based on several factors such as the current value of the observables, the short-term meteorological information, the expected demand etc. Based on this prediction, the cell state estimation system, launching a state estimation algorithm, calculates the anticipated state of the cell on a CTS3 horizon. If a "future" voltage error is foreseen, the necessary PPVC reserves take action in order to mitigate future voltage imbalances. The process for checking PPVC availability as well as PPVC selection and activation of the required PPVC resources is equal to the one described for the first scenario.

As a conclusion for the explanation of the two scenarios, the table 15 serves as a summary chart of the inputs and outputs of the controllers involved in the PPVC loops.

Table 15

Controller	Objective	Input (Observable)	Output	Timing
Cell State Estimation System	Sc1: Calculation of the cell state from a state estimation process	Sc1: Voltage phasors (RMS, phase) and complex power	Sc1: Real cell state	Sc1 & Sc2: continuously running
	Sc2: Calculation of the estimated cell state from a state estimation process	Sc2: Foreseen value of the voltage phasors (RMS, phase) and complex power	Sc2: Estimated cell state	Sc1 & Sc2: Every 15 min minutes (CTS3)
Cell Operator	Sc1 & Sc2: Provision of an activation signal for the more cost-effective PPVC resources currently available	Sc1: Voltage error detected in any cell node	Sc1 & Sc2: PPVC activation signal for the PPVC reserve providers (or the Flexibility resources)	Sc1 & Sc2: In the order of minutes (CTS2)
		Sc2: Expected voltage error in a cell node		
PPVC Resource Provider	Sc1 & Sc2: Activation of the Flexibility resources available	Sc1 & Sc2: Confirmation of Flexibility Resource availability (Flexibility signal)	Sc1 & Sc2: Activation signal downstream to the available Flexible Resources	Sc1 & Sc2: In the order of minutes (CTS2)
Flexibility resource	Sc1 & Sc2: Response to the activation signal	Sc1 & Sc2: Depending on the control mode: voltage set-point, reactive (or active) power set-point, power factor set-point.	Sc1 & Sc2: Corresponding change in the voltage, power of power factor.	Sc1 & Sc2: In the order of minutes (CTS2)

5 Preference List of Use Cases to be tested in the lab

In the next list, the main use cases are listed with a ranking of innovative solutions.

Main Use Case	Innovative elements	Ranking (1-5)
B1.Inertia Response Power Control (IRPC)	• Inertia observation • Inertia control	5
B2.Frequency Containment Control (FCC)	• <xx>	
B3.Balance Restoration Control (BRC)	• <xx>	
B4.Balance Steering Control (BSC)	• <xx>	
T1.Primary Voltage Control (PVC)	• <xx>	1
T2.Post-primary Voltage Control (PPVC)	• <xx>	2

From the list above, a choice can be made for the lab tests in WP7.

6 Conclusions

This first part of T6.2 "*Functional specification of the control functions for the control of flexibility across the different control boundaries*" concentrates on several activities:

- Control architecture and design principles
- A taxonomy of control mechanisms
- Working procedure for selecting Control Triples, that can be used as building blocks in the high level Use Cases
- General black box functions and interface to other ELECTRA WPs
- Control relations in the Web-of-Cells power system
- Use Case composition of control functions, based on the selected control triples.

The document outlines a methodology specifically created for developing and testing control algorithms 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 future power system with a high share of RES requires rethinking of several well-established fundamental principles in the power system domain. Instead of conventional voltage and frequency controls, Balance and Voltage types of control have been introduced. These require introduction of several new terms of definitions, which have been proposed in cooperation with WP5. Some of these have been further developed from the previous Tasks, such as Control Time Scales (CTSs), while the others are new, such as Control Topology Levels (CTLs).

Among the major novelties are the planned use of SRPS grid models for simulations, and a structured methodology incorporating the concept of control triples and quadruples in the black box control loop description that is input to the Use Case method.

The results so far also indicate that the WoC concept, together with the above mentioned methodology built on top of the well-known Use Case methodology, allow for determining control functions for an electric power system supporting future energy systems in a tractable manner.

In the following implementation part , the control functions identified will be tested in SRPS simulations so that these further can be implemented by WP4 in an SGAM based IT architecture. In WP7, relevant parts of the resulting system concepts will be testing in laboratory demonstrations.

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8 Disclaimer

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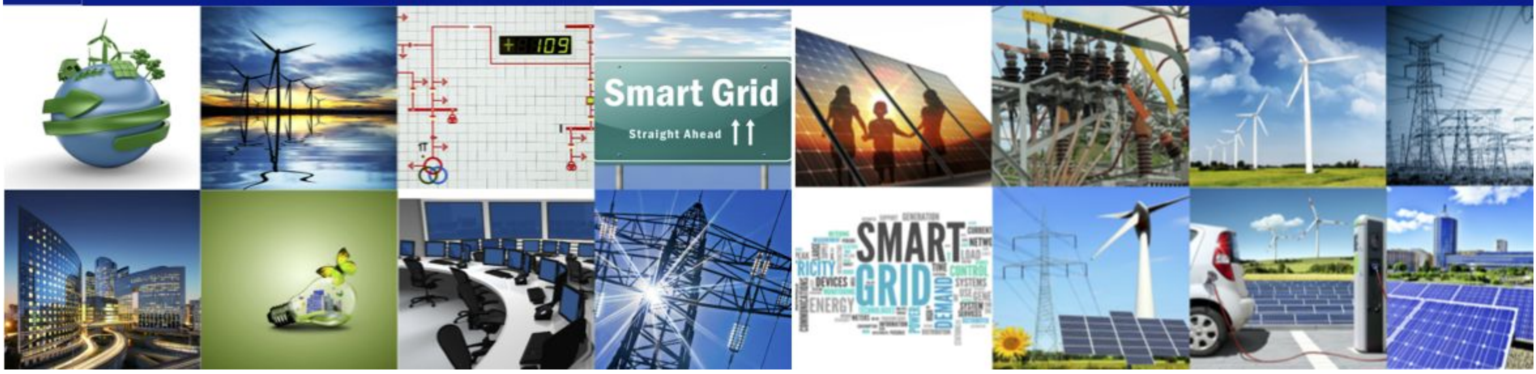
FP7-ENERGY-2013-IRP

ELECTRA

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



WP 6

Control schemes for the use of Flexibility

Deliverable 6.1

Functional specification of the control functions for the control of flexibility across the different control boundaries

<Annex: Selected conceptual solutions for Balance and Voltage Control>

20/Dec/2015

Index

1. Inertia Steering Control

D3.1 formulated objective : The objective is to maintain, both in case of a power imbalance (positive or negative) and during normal operation, within the limits of a reference incident the frequency quality parameters of maximum allowed dfmax/dt and maximum dynamic frequency deviation limit Δfdyn,max.

For frequency incidents, maintaining is done until downstream functionalities take over to contain and to restore system frequency by means of Frequency Containment Control, Balance Restoration Control and Balance Steering Control.

For normal operation, maintaining is done until the dynamic frequency deviations return to nominal or lower without additional inertial response power.

Reformulated Objective(s) :

- ***Decompose the cell's requested Virtual Inertia contribution setpoint (e.g. received from a synchronous area Virtual Inertia controller at T_0/T_i) into virtual inertia providing settings for contributing virtual inertia providing reserves in the cell, to ensure cost effective and grid secure virtual inertia provisions taking into account the cell's internal state.***
- ***Contain frequency fluctuations (Δf_{RMS}) and limit ROCOF ($\Delta f/\Delta t$) in the system by providing sufficient (virtual) inertia in the absence of physical inertia (rotating mass).***

1.1 Specific control aims: possible variants

- Keep $\Delta f/\Delta t$ (Δf_{RMS}) below a threshold value.
- Keep Δf_{RMS} below a threshold value.

Note 1: Inertia smoothens the fast small stochastic frequency fluctuations that occur because of the stochastic effect of many small instantaneous imbalances. It as well reduces the Rate of Change of Frequency (ROCOF) thereby limiting (avoiding) FCC activations as well as containing frequency deviations until the slower FFC can correct them. As the fluctuations are small, fast varying and stochastic, the reserves providing resources must be power-capable rather than energy capable.

Note 2: The future power system will be confronted with strong (but slowly) varying inertia due to seasonal to intra-day varying energy mixes (day versus night, summer versus winter, windy day versus calm day, sunny day versus cloudy day, …). Because of these inertia fluctuations a same system imbalance may result in very different frequency deviations and in case of a (too) low amount of inertia, a too large frequency deviation might occur before it can be contained by the slower FCC control.

Note 3 : Depending on the specific future requirement on frequency stability (what are the allowed frequency bands, how fast must they be restored), and the speed of BRC, BRC might be considered to be the 'primary response' as it, by restoring cell balances, also restores the system balance hence system frequency. The higher the (virtual) inertia, the more time BRC has for a corrective action, and the less need there is for an FCC.

Note 4 : Typically, a cell receives an Inertia (H) setpoint based on some cell characteristics (for the next control time window), and based on this the H setpoint is decomposed in $\Delta P/(\Delta f_{RMS}$ or $\Delta f/\Delta t)$ droop slope setpoints for the virtual inertia providing resources. In contrast FCC, there probably is no need for an adaptive *setting that takes into account a cell's balance status, as activations are stochastically fast varying (around 0) and small compared to FCC activations.*[CC1]

$\|\Delta fRMS\| < \|\Delta fRMS\|_{thres.}$	CA1
$\|\Delta f/\Delta t\| < \|\Delta f/\Delta t\|_{thres.}$	CA2

Note : both of these two CAs must be fulfilled at the same time : they are complementary.

1.2 Architectural options for IRPC specific control aims

Note : We focus here on the most basic architectural variants that directly impact the technicality of the solutions (observables and controls). Additional variants that focus more on the practical implementation e.g. related to the scalability of the solution – e.g. aggregators that aggregate multiple reserves providing resources – are not considered here as these would lead to unnecessary complexity and an explosion of the variant space. Such specific variants – where relevant – will be added in the subsequent whiteboxing and implementation phase.

1.2.1 Control Loop Architecture

- Decentral monitor/Decentral controller (autonomous distributed control).

Note: this relates specifically to the continuous virtual inertia droop control itself ; not to the H decomposition into device droop slopes with is done by a central function.

1.2.2 Cell H Determination

- Cell central function receives a cell-level H setpoint at T_i

1.2.3 Controller Type

- P-controller (proportional) : as a subclass (design time variants during whiteboxing) a fuzzy or robust controller could be considered.

1.2.4 Droop slope determination for H reserves based on cell H setpoint : four variants

- Cell central function determines the droop slope (direct, merit order based) <u>versus</u> cell central function clears bids (indirect, bid based) <u>versus</u> cell central function negotiates bids <u>versus</u> resources determine their own droop slope in a multi-agent iterative negotiation process without central controller

1.3 IRPC variants (4 variants)

Variant	Control Loop Architecture	Cell H Determination	Controller Type	Droop Sloop Determination			
	Decentr.Mon, Decentral Contr.	Setpoint received at T_i	P (Fuzzy/ $H^2/H^{¥}$)	Cell Central ; merit order ; direct	Cell central ; bid clearing ; indirect	Cell central ; bid negotiation ; direct	Distributed ; Negotiation
IRPC1.1	X	X	X	X			
IRPC1.2	X	X	X		X		
IRPC1.3	X	X	X			X	
IRPC1.4	X	X	X				X

Preliminary proposed selection of variants that will be elaborated further (whiteboxing/design, implementation and testing in combination with the other controls) : this selection may be narrowed further after discussion with the other UC writing teams:

- All four variants seem interesting to pursue for now.

1.4 Black Box functions needed

1.4.1 Frequency Fluctuation Observing function

Each reserves providing resource has a function that continuously samples voltage waveforms to calculate the Δf_{RMS} and ROCOF ($\Delta f/\Delta t$) of the system frequency. This can be at either the connection point of a single device or a Point of Common Coupling of the aggregated resource.

- Input : Voltage waveforms *(continuously)*
- What : Calculate Δf_{RMS} and ROCOF ($\Delta f/\Delta t$) from the input signals *(as fast as possible)*
- Output :Actual value of frequency *(as fast and often as possible)*

Note : we focus on voltage waveforms although of course also the rotating speed of remaining synchronous generators could still be used.

1.4.2 IRPC Controlling function

Each reserves providing resource has a function that continuously calculates the error signals for Δf_{RMS} and ROCOF ($\Delta f/\Delta t$) , and based on this and its droop slope, it increases or decreases active power generation/consumption in a proportional manner to counter the frequency fluctuation.

- Input : Δf_{RMS} and ROCOF ($\Delta f/\Delta t$) setpoints, instantaneous value of frequency (as fast and often as possible), Droop Slope (H value decomposed from the cell's setpoint H value)

- What : Increase/Decrease active power generation/consumption according to the measured error signals and the droop slope (continuously)
- Output : Increased/Decreased active power generation/consumption (continuously).

Note : As a design time variant (whiteboxing) we could make the IRPC controller aware of the congestion situation at its connection point, and let it locally decide to alter its response ; TBD if this added complexity makes sense given the small and stochastic nature of the activations.

1.4.3 **Merit Order Building** function

This cell central function builds a merit order based on the information received by the Cell State Estimation function and the Reserves Status Informing function. The merit order not only takes into account the cost of an activation, but as well the cell state estimation and the location of the reserves providing resource in the cell (*TBD how relevant this is, given the small and stochastic nature of the activations*), so that (normally) all activations can be done in a grid secure manner.

- Input : cell state estimation, reserves available (capabilities and constraints, cost, location)
- What : Determines a location and cell state aware merit order list
- Output : an ordered list of reserves to be activated (which one and how much and/or according to what profile)

Note : we assume that the Merit Order Building function also takes into account location information (e.g. through some sort of registry : see OS4ES) so that a congestion avoiding merit order can be calculated. In the next steps we could decide to elaborate additional (exceptional) scenarios where this is not the case i.e. no location information is used (but then also the cell state is not needed ?) or even though this is used, congestions can still occur.

1.4.4 **Device Droop Slope Determination** function (4 variants)

This cell-central function determines the droop slope of available IRPC devices by decomposing the cell's H setpoint into device droop slopes in such a manner that the aggregated droop slope is equal (or larger) than the cell's decided H contribution, taking into account activation cost and grid security. It will ensure that for each timestep the worst case activation will be grid secure by taking into account the cell state time vector information and the effect of a worst case activation on this.

Variant 1 : Central/Merit Order/Direct:

- Input : cell H set-point (for control time window, at T_i), Merit Order list
- What : determine device droop slopes based on the merit order list
- Output : Droop slope for each IRPC device (this could a either a constant value for the complete control time window, but this even could be a profile, at T_i).

Note : It is assumed that the merit order ensures secure activations by taking grid state and resource locations explicitly into account. Scenarios that deal with exceptions can be added as deemed interesting.

Note : the proposal is to define slope profiles : a fixed slope is then just a special case.

Variant 2 : Central/Bid Clearing/Indirect:

- Input : cell H setpoint (for control time window, at Ti), IRPC device bids containing availability/cost (for control time window, at Ti)
- What : Based on received bids that contain information on what can be offered for what incentive and how much is required, a (virtual) market clearing is done that determines the incentive signal that will be provided to the resources based on which these know what slope they are expected to provide (indirect slope setting). If also location information is provided, first those bids that are in congested segments could be filtered

out before doing the market clearing. Or better : their bids can be 'capped' in such a way that an activation would not cause a congestion).

- Output : Incentive signal to each IRPC devices from which each device can derive its droop slope (for control time window, at T_i).

Note : It is assumed that the bids contain location information and that as a result the bid clearing only takes into account bids that would result in a secure activation. Scenarios that deal with exceptions can be added as deemed interesting.

Variant 3 : Central/Bid Negotiation/Direct:

- Input : cell H setpoint (for control time window, at T_i), IRPC device bids containing availability/cost (for control time window, at T_i)
- What : Based on received bids that contain information on what can be offered for what incentive and how much is required, a (virtual) market clearing is done that determines the incentive signal. Next a negotiation process starts to encourage resources of lower their requested incentive. This negotiation process results in the end in a direct slope setting command to the resources.
- Output : Incentive signal to each IRPC device from which each device can derive its droop slope (for control time window, at T_i).

Variant 4 : Distributed/Negotiation:

- Input : each IRPC device receives the cell's H setpoint (for control time window, at T_i)
- What : Based on the required cell H setpoint (and cell state estimation ?) each device proposes a slope and associated expected incentive (taking into account its location and the cell state estimation) and broadcasts this to all other devices. This way each device gets a view on what the aggregated slope and cost would be of their aggregated proposal, and based on that each device updates its proposal and broadcasts this again. Until a certain acceptable result is achieved.
- Output : Droop slope for each IRPC device (this could a either a constant value for the complete control time window, but this even could be a profile, at T_i).

1.4.5 Cell State Estimation function

This cell central function builds a forecasted estimate of the cell's grid state (bus voltages and line flows) to be used by the Merit Order Building function.

- Input : grid topology with connection points, bus voltages (dynamic measurement) and line flows (dynamic measurement), other TBD information
- What : forecast grid state for the next TBD time window.
- Output : Estimated bus voltages and line flows for the next TBD time window (a time vector with values for each bus)

Note : further discussion is needed on whether the forecasted estimate is based on bus measurements only, or whether additional information - and which one - is needed (e.g. updated weather forecasts) e.g. to update forecasted deviations in connection points or on the cell as a whole.

Note : further discussion is needed on what machine-learning technology could be applied for such cell state estimation.

Note : further discussion is needed on whether this is only done once in each control time window, or whether this is repeated regularly.

1.4.6 Reserves Status Informing function

Each reserves providing resource (and the aggregator) provides updated information on its reserves providing capabilities for the next time window as well as associated cost.

- Input : None (local information)
- What : Determine how much (max power slope ; either a constant or a profile) it can provide
- Output : a description of how much power it can provide for what cost, and its location

  Note : Strictly speaking we need here variants depending on what information is given for what purpose (e.g. for merit order building versus bid versus …). This additional level of detail will be added during the whiteboxing.

1.4.7 Power Steering function

Each reserves providing resource has a function that increases/decreases its power generation/consumption as requested.

- Input : power activation signal
- What : increases/decreases power generation/consumption as requested
- Output : increased/decreased power generation/consumption

1.5 Selection Description

1.5.1 IRPC1.1

Short description

In this variant conceptual solution, the cell's Virtual Inertia contribution is a fixed setpoint for the duration of the control time window. This cell Virtual Inertia contribution is decomposed into device droop slopes by means of a merit order decision process. The IRPC at the devices act on measured frequency fluctuations to activate power to virtually increase/decrease inertia.

Black Box functions

- Cell H Setpoint Informing *(not in scope)*
- Cell State Estimation
- Device Droop Slope Determination: variant 1 (Central / Merit Order / Direct)
- Reserves Status Informing
- IRPC Controlling
- Frequency Fluctuation Observing
- Power Steering

1.5.2 IRPC1.2

Short description

In this variant conceptual solution, the cell's Virtual Inertia contribution is a fixed setpoint for the duration of the control time window. Device droop slopes are determined by means of a bid clearing process. The IRPC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell H Setpoint Informing *(not in scope)*
- Cell State Estimation
- Device Droop Slope Determination: variant 2 (Central / Bid Clearing / Indirect)
- Reserves Status Informing

- IRPC Controlling
- Frequency Fluctuation Observing
- Power Steering

1.5.3 IRPC1.3

Short description

In this variant conceptual solution, the cell's Virtual Inertia contribution is a fixed setpoint for the duration of the control time window. The device droop slopes are determined by means of a cell central managed negotiation. The IRPC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell NPFC Setpoint Informing *(not in scope)*
- Device Droop Slope Determination: variant 3 (Negotiation)
- IRPC Controlling
- Frequency Fluctuation Observing
- Power Steering

1.5.4 IRPC1.4

Short description

In this variant conceptual solution, the cell's Virtual Inertia contribution is a fixed setpoint for the duration of the control time window. The device droop slopes are determined by means of a distributed negotiation. The IRPC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell NPFC Setpoint Informing *(not in scope)*
- Device Droop Slope Determination: variant 4 (Distributed / Negotiation)
- IRPC Controlling
- Frequency Fluctuation Observing
- Power Steering

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2. Frequency Containment Control

D3.1 formulated objective : In case of a power imbalance (positive or negative) within the limits of a reference incident the objectives are:

- ***To support Inertia response power Control in order to keep the frequency quality parameter maximum dynamic frequency deviation limit $\Delta f_{dyn,max}$***
- ***To keep the maximum steady-state frequency deviation $\Delta f_{dyn,static}$ until downstream functionalities take over to restore system frequency by means of Balance Restoration Control and Balance Steering Control.***

Reformulated Objective(s) :

- ***Decompose the cell's requested NPFC contribution setpoint (e.g. received from a synchronous area NPFC controller at T_0/T_i) into droop slope settings for contributing FCC reserves in the cell, to ensure cost effective and grid secure FCC activations taking into account the cell's internal state.***
- ***Contain Frequency deviations (limit to $\Delta f_{dyn,max}$) in the system when (large) system imbalances (total system generation <> total system load) happen***

1.1 Specific control aims: possible variants

- Continuous Frequency Regulation **($|\Delta f|>0$)**: respond to even the slightest frequency deviation so as to provide a fine-grained regulation of frequency even when small system imbalances happen
- Frequency Regulation with deadband **($|\Delta f|>|\Delta f|_{thres}$)**: In this case the FCC reserves are not instantly activated at the slightest frequency deviation but only when Δf exceeds a specific threshold.

Note 1 :The future role and requirements related to frequency control merits still more discussion that is ongoing between the partners and with external stakeholders (e.g. the Joint ELECTRA/ETP-SG workshop on December 10th 2015). Does frequency still needs to be contained in the same narrow bands as today ? Role of Inertia Steering versus FCC for constraining frequency deviations ? What is the real objective : Frequency Containment or System Imbalance Containment : where frequency WAS just a convenient observable for system imbalances ? Is frequency in the future still a convenient observable, given the decline of synchronous generators that offer a physical electric-to-kinetic energy transformations as an observable ? Next to questions related to impact on stranded assets (like protection equipment) and cost-benefit analysis (stranded assets versus inertia steering and/or FCC) it may be interesting to assess BRC with and without FCC to assess the technical implications and requirements.

Note 2 : In the WoC concept, BRC might be considered to be the 'primary response' as it, by restoring cell balances, also restores the system balance hence system frequency. The reason why this might be sufficient, is that by the use of new types of devices (very large amounts of distributed fast acting reserves) this might be 'fast enough' to also ensure frequency containment (in contrast to today's secondary frequency control which also is powerflow and CA/CB balance based, but is too slow to act as primary control). So we need FCC in case (of large incidents when) BRC would not restore the frequency fast enough. ***Questions are : What is 'fast enough' ? Do we still need frequency containment in today's bands or can this be relaxed ? What is the appropriateness of frequency deviation as a measure of system imbalance in a power***

system with no or a limited amount of synchronous generators ? If we need to add virtual inertia anyway, frequency containment could be achieved by increasing inertia as opposed to having an FCC that causes additional cell imbalances (at least : technically speaking).

Note 3 : If all cells are in balance (generate and consume according to their setpoint which is determined to provide a system balance), also the system is in balance. Due to the imbalance netting effect, it would require much more activations to restore all cell balances than to restore system balance. This is where the BSC comes into play, by reducing the amount of activations and allowing cell imbalances if this can be done in a grid secure manner.

Note 4 : FCC acts on a global observable for the System Imbalance (Generation <> Load) instead of a cell local observable, and therefore it may cause – or worsen – cell imbalances of cells that otherwise would be in balance.
Note 5 : Typically, a cell receives an NPFC setpoint based on some cell characteristics (for the next control time window), and based on this the NPFC setpoint is decomposed in droop slope setpoints for the FCC resources. If a cell's NPFC could be adjusted to take into account a cell's balance status, this could be a way to introduce 'locality and proportionality' into FCC i.e. ensure that cells that are in balance (i.e. are operating according to their setpoint) do not activate FCC that introduces imbalances. ***The question is : how to ensure then that the aggregated NPFC of all cells is sufficient ? Can this be done without a central controller that oversees all the cells e.g. by means of a distributed algorithm ?***

$\|\Delta f\| > 0$	CA1
$\|\Delta f\| > \|\Delta f\|_{thres.}$	CA2

1.2 Architectural options for FCC specific control aims

Note : We focus here on the most basic architectural variants that directly impact the technicality of the solutions (observables and controls). Additional variants that focus more on the practical implementation e.g. related to the scalability of the solution – e.g. aggregators that aggregate multiple reserves providing resources – are not considered here as these would lead to unnecessary complexity and an explosion of the variant space. Such specific variants – where relevant – will be added in the subsequent whiteboxing and implementation phase.

1.2.1 Control Loop Architecture

- Decentral monitor/Decentral controller (autonomous distributed control).

Note : this relates specifically to the continuous FCC control itself ; not to the NPFC (determination and) decomposition into device droop slopes with is done by a central function.

1.2.2 Cell NPFC Determination : two variants

- Cell central function receives a cell-level NPFC setpoint at T_i <u>versus</u> cell central function adapts the cell's NPFC based on the cell's imbalance (deviation from cell balance setpoint).

1.2.3 Controller Type

- P-controller (proportional) : as a subclass (design time variants during whiteboxing) a fuzzy or robust controller could be considered.

1.2.4 Droop slope determination for FCC reserves based on cell NPFC : four variants

- Cell central function determines the droop slope (direct, merit order based) <u>versus</u> cell central function clears bids (indirect, bid based) <u>versus</u> cell central function negotiates bids <u>versus</u> resources determine their own droop slope in a multi-agent iterative negotiation process without central controller

1.3 FCC variants (16 variants)

<u>For CA1 (x = 1) and CA2 (x = 2)</u>

	Control Loop Architecture	Cell NPFC Determination		Controller Type	Droop Sloop Determination			
Variant	Decentr. Mon, Decentral Contr.	Setpoint received at T_i	Setpoint adaptation based on cell balance error signal	P (Fuzzy/ H^2/H¥)	Cell Central ; merit order ; direct	Cell central ; bid clearing ; indirect	Cell central ; bid negotiation ; direct	Distributed ; Negotiation
FCCx.1	**X**	**X**		**X**	**X**			
FCCx.2	**X**	**X**		**X**		**X**		
FCCx.3	X	X		X			X	
FCCx.4	**X**	**X**		**X**				**X**
FCCx.5	**X**		**X**	**X**	**X**			
FCCx.6	X		X	X		X		
FCCx.7	X		X	X			X	
FCCx.8	X		X	X				X

Preliminary proposed selection of variants that will be elaborated further (whiteboxing/design, implementation and testing in combination with the other controls) : this selection may be narrowed further after discussion with the other UC writing teams:

- The variants selected for further elaboration are all from CA2, namely FCC control with threshold value in the frequency signal. These variants are more general as they also cover CA1 variants, which may as well be considered special cases of CA2 ones with a threshold frequency 0.
- Three of the four selected variants implement the case where the cell receives an NPFC setpoint value at T_i that the cell should provide in order to meet the system requirements. Of these three variants **FCC2.1** is selected as the case where a merit-order activation is obtained centrally. **FCC2.2** represents the case of central activation by an indirect signal of incentives to the resources. Finally, **FCC2.4** is used as a variant representative of distributed control, namely active negotiation and participation of resources in the activation procedure.
- As an alternative to the above solutions, variant **FCC2.5** is also considered for further analysis. This variant takes into account the cell's imbalance state and attempts to selectively implement FCC in to avoid or mitigate cell-imbalance causing or worsening FCC activations.

1.4 Black Box functions needed

1.4.1 Frequency Observer function

Each reserves providing resource has a function that continuously samples voltage waveforms to calculate the instantaneous value of the system frequency. This can be at either the connection point of a single device or a Point of Common Coupling of the aggregated resource.

- Input : Voltage waveforms *(continuously)*
- What : Calculate actual frequency from the input signals *(as fast as possible)*
- Output :Actual value of frequency *(as fast and often as possible)*

Note : we focus on voltage waveforms although of course also the rotating speed of remaining synchronous generators could still be used.

1.4.2 FCC Controller without/with deadband function (2 variants)

Each reserves providing resource has a function that continuously calculates the frequency error signal, taking into account the optional deadband, and based on this and its droop slope, increases or decreases active power generation/consumption in a proportional manner to counter the frequency deviation / system imbalance.

- Input : frequency set-point (could be constant ; otherwise at the beginning of each control time window at Ti), instantaneous value of frequency (as fast and often as possible), Droop Slope (either at beginning of each control time window at Ti – for FCCx.1-4 – or as often as possible – for FCCx.5-8)
- What : Increase/Decrease active power generation/consumption according to the frequency error signal (with or without deadband : two variants) and the droop slope (continuously)
- Output : Increased/Decreased active power generation/consumption (continuously).

Note : As a design time variant (whiteboxing) we could make the FCC controller aware of the congestion situation at its connection point, and let it locally decide to alter its response (Pc signal that shifts the droop up and down) : of course this could result in less FCC resources that are activated and we must ensure that this does not result in system instability.

1.4.3 Adaptive Cell NPFC Determination function (only for FCCx.5-8)

This cell central function adapts the cells NPFC based on the cell's imbalance error signal (from BRC : possibly corrected for the FCC activations). The challenge is how this can be done – in real-time, and without a system-level central controller – in such a manner that the aggregated NPFC of all cells remains sufficient.

- Input : initial NPFC value, Cell Balance error signal
- What : Calculate adapted NPFC
- Output : Adapted NPFC (+ coordination signal with neighbours to ensure sufficient NPFC remains available at cell level)

Note : the initial NPFC at the beginning of the control time window can be provided by a system central function, or it can be inherited from the previous control time window.

Note : can redistribution of the required system level NPFC be accomplished through a distributed neighbour-to-neighbour algorithm ? Alternatively to initial NPFC could be high enough such that if certain cells decrease their NPFC there still is sufficient NPFC at system level remaining.

1.4.4 Merit Order Building function

This cell central function builds a merit order based on the information received by the Cell State Estimation function and the Reserves Status Informing function. The merit order not only takes into account the cost of an activation, but as well the cell state estimation and the location of the reserves providing resource in the cell, so that (normally) all activations can be done in a grid secure manner.

- Input : cell state estimation, reserves available (capabilities and constraints, cost, location)
- What : Determines a location and cell state aware merit order list
- Output : an ordered list of reserves to be activated (which one and how much and/or according to what profile)

Note : we assume that the Merit Order Building function also takes into account location information (e.g. through some sort of registry : see OS4ES) so that a congestion avoiding merit order can be calculated. In the next steps we could decide to elaborate additional (exceptional) scenarios where this is not the case i.e. no location information is used (but then also the cell state is not needed ?) or even though this is used, congestions can still occur.

1.4.5 Device Droop Slope Determination function (4 variants)

This cell-central function determines the droop slope of available FCC devices by decomposing the cell's NFPC into device droop slopes in such a manner that the aggregated droop slope is equal (or larger) than the cell's decided NPFC contribution, taking into account activation cost and grid security. It will ensure that for each timestep the worst case activation will be grid secure by taking into account the cell state time vector information and the effect of a worst case activation on this.

Variant 1 : Central/Merit Order/Direct:

- Input : cell NPFC set-point (for control time window, at T_i), Merit Order list
- What : determine device droop slopes based on the merit order list
- Output : Droop slope for each FCC device (this could a either a constant value for the complete control time window, but this even could be a profile, at T_i).

Note : It is assumed that the merit order ensures secure activations by taking grid state and resource locations explicitly into account. Scenarios that deal with exceptions can be added as deemed interesting.

Note : the proposal is to define slope profiles : a fixed slope is then just a special case.

Variant 2 : Central/Bid Clearing/Indirect:

- Input : cell NPFC setpoint (for control time window, at T_i), FCC device bids containing availability/cost (for control time window, at T_i)
- What : Based on received bids that contain information on what can be offered for what incentive and how much is required, a (virtual) market clearing is done that determines the incentive signal that will be provided to the resources based on which these know what slope they are expected to provide (indirect slope setting). If also location information is provided, first those bids that are in congested segments could be filtered out before doing the market clearing. Or better : their bids can be 'capped' in such a way that an activation would not cause a congestion).
- Output : Incentive signal to each FCC devices from which each device can derive its droop slope (for control time window, at T_i).

Note : It is assumed that the bids contain location information and that as a result the bid clearing only takes into account bids that would result in a secure activation. Scenarios that deal with exceptions can be added as deemed interesting.

Variant 3 : Central/Bid Negotiation/Direct:

- Input : cell NPFC setpoint (for control time window, at T_i), FCC device bids containing availability/cost (for control time window, at T_i)
- What : Based on received bids that contain information on what can be offered for what incentive and how much is required, a (virtual) market clearing is done that determines the incentive signal. Next a negotiation process starts to encourage resources of lower their requested incentive. This negotiation process results in the end in a direct slope setting command to the resources.
- Output : Incentive signal to each FCC devices from which each device can derive its droop slope (for control time window, at T_i).

Variant 4 : Distributed/Negotiation:

- Input : each FCC device receives the cell's NPFC setpoint (for control time window, at Ti)
- What : Based on the required cell NPFC setpoint (and cell state estimation ?) each device proposes a slope and associated expected incentive (taking into account its location and the cell state estimation) and broadcasts this to all other devices. This way each device gets a view on what the aggregated slope and cost would be of their aggregated proposal, and based on that each device updates its proposal and broadcasts this again. Until a certain acceptable result is achieved.
- Output : Droop slope for each FCC device (this could a either a constant value for the complete control time window, but this even could be a profile, at Ti).

1.4.6 Cell State Estimation function

This cell central function builds a forecasted estimate of the cell's grid state (bus voltages and line flows) to be used by the Merit Order Building function.

- Input : grid topology with connection points, bus voltages (dynamic measurement) and line flows (dynamic measurement), other TBD information
- What : forecast grid state for the next TBD time window.
- Output : Estimated bus voltages and line flows for the next TBD time window (a time vector with values for each bus)

Note : further discussion is needed on whether the forecasted estimate is based on bus measurements only, or whether additional information - and which one - is needed (e.g. updated weather forecasts) e.g. to update forecasted deviations in connection points or on the cell as a whole.

Note : further discussion is needed on what machine-learning technology could be applied for such cell state estimation.
Note : further discussion is needed on whether this is only done once in each control time window, or whether this is repeated regularly.

1.4.7 Reserves Status Informing function

Each reserves providing resource (and the aggregator) provides updated information on its reserves providing capabilities for the next time window as well as associated cost.

- Input : None (local information)
- What : Determine how much (max power slope ; either a constant or a profile) it can provide
- Output : a description of how much power it can provide for what cost, and its location

Note : Strictly speaking we need here variants depending on what information is given for what purpose (e.g. for merit order building versus bid versus …). This additional level of detail will be added during the whiteboxing.

1.4.8 Power Steering function

Each reserves providing resource has a function that increases/decreases its power generation/consumption as requested.

- Input : power activation signal
- What : increases/decreases power generation/consumption as requested
- Output : increased/decreased power generation/consumption

1.5 Selection Description (incl. MSCs)

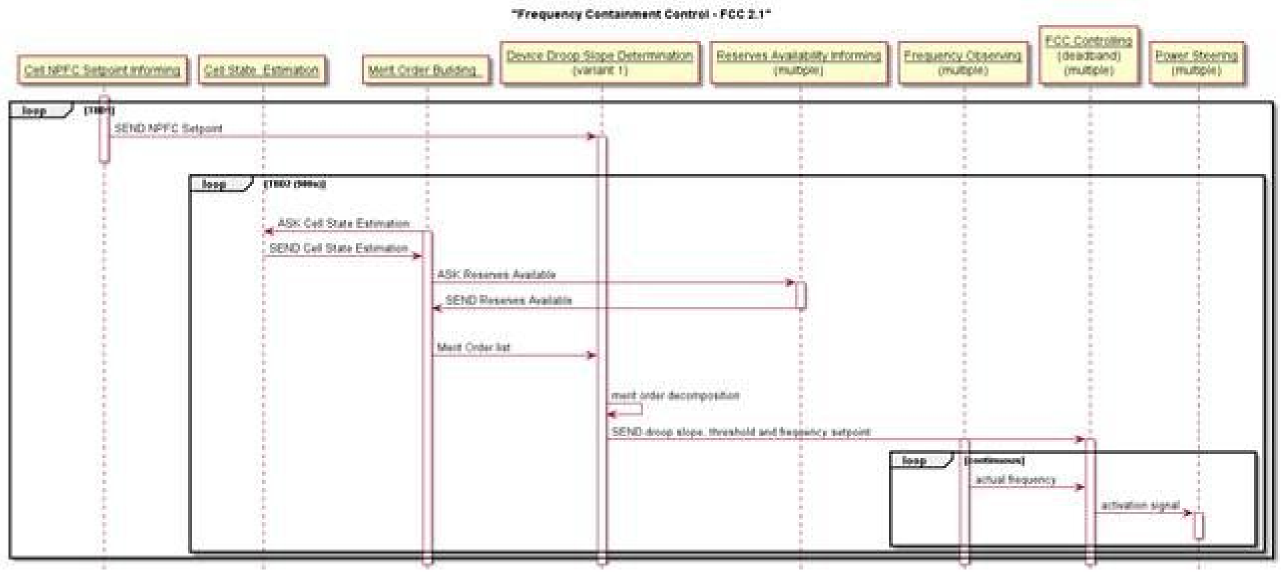
1.5.1 FCC2.1 : FCC with frequency threshold and central/merit order/direct NPFC decomposition

Short description

In this variant conceptual solution, the cell's NPFC is a fixed setpoint for the duration of the control time window. This cell NPFC is decomposed into device droop slopes by means of a merit order decision process. The FCC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell NPFC Setpoint Informing *(not in scope)*
- Cell State Estimation
- Device Droop Slope Determination: variant 1 (Central / Merit Order / Direct)
- Reserves Status Informing
- FCC Controlling with deadband
- Frequency Observing
- Power Steering



Note : For the inner (continuous) loop : this is active all the time ; until a new droop slope etc is received, it operates based on the previous setting.

Information Exchanges (example : will be elaborated in D4.2)

- *NPFC Setpoint : a value that gives the required aggregated droop slope of all devices (KW/Hz) : a constant value for the complete time window ; as more advanced functiuonality a profile could be considered.*
- *Cell State Estimation : a time vector (resolution TBD) where for each bus the estimated/forecasted voltage and current is given (based on knowledge or forecast or model of generation and load profiles at each connection point)*
- *Reserves Available (from each device) : the max power/slope it can provide, the max energy it can provide (this will determine how long it can provide how much power depending on the slope), the requested reward*
- *Droop Slope (for each device) : KW to be increased/decreased per Hz deviation*
- *Frequency setpoint (optional) and deadband (for each device) : Hz*

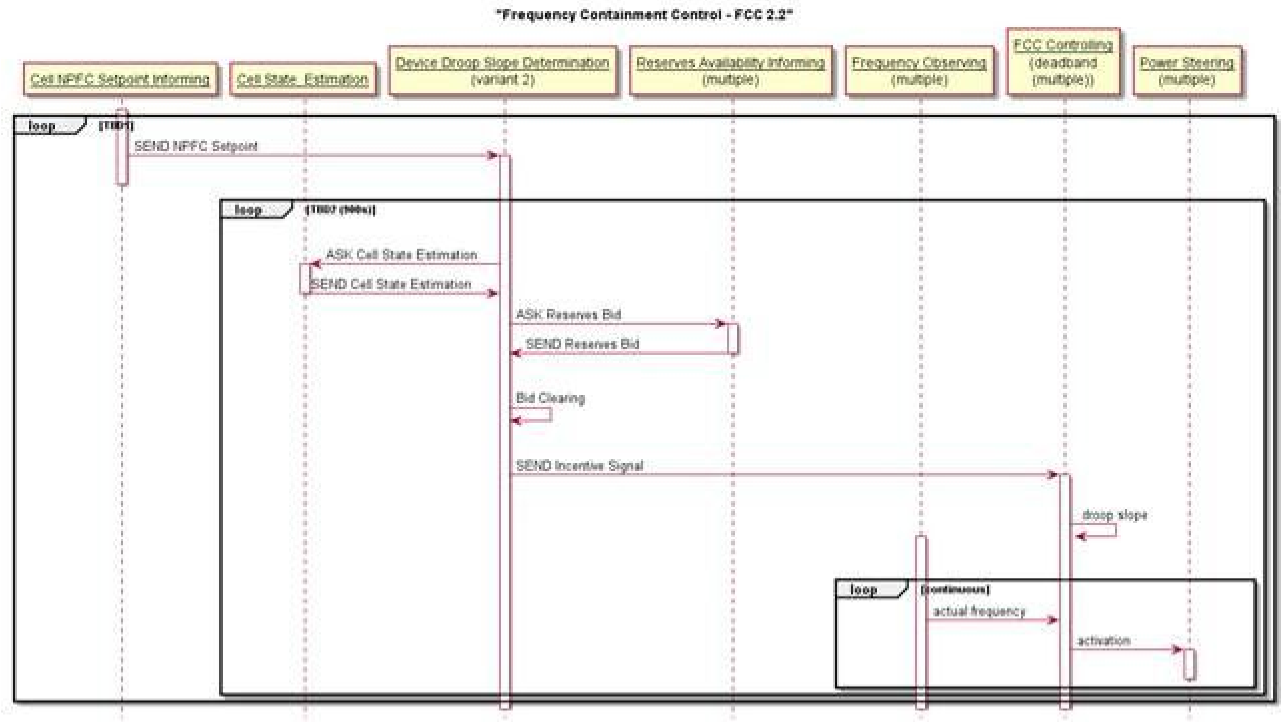
1.5.2 FCC2.2 : FCC with frequency threshold and central/bid clearing/indirect NPFC decomposition

Short description

In this variant conceptual solution, the cell's NPFC is a fixed setpoint for the duration of the control time window. The device droop slopes are determined by means of a bid clearing process. The FCC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell NPFC Setpoint Informing *(not in scope)*
- Cell State Estimation
- Device Droop Slope Determination: variant 2 (Central / Bid Clearing / Indirect)
- Reserves Status Informing
- FCC Controlling with deadband
- Frequency Observing
- Power Steering



Note : For the inner (continuous) loop : this is active all the time ; until a new incentive signal is received, it operates based on the previous setting.

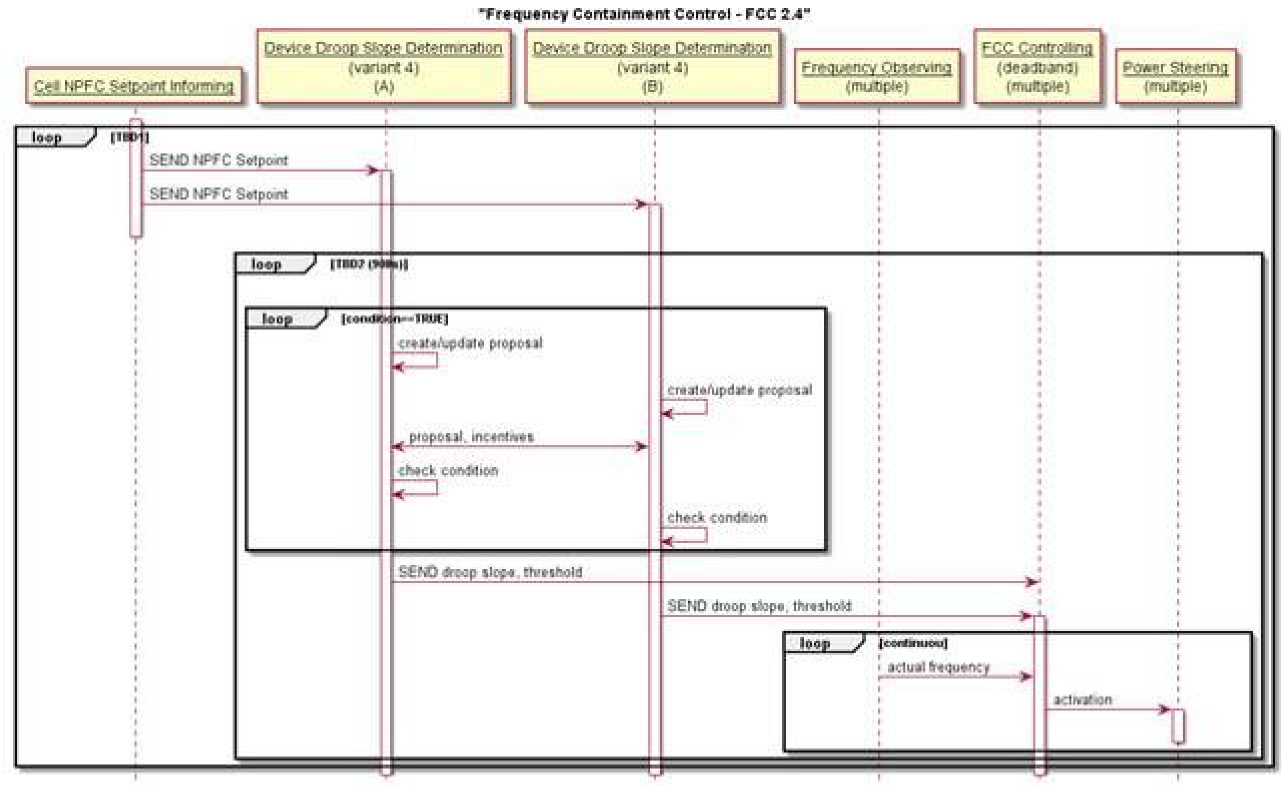
1.5.3 FCC2.4 : FCC with frequency threshold and distributed/indirect NPFC decomposition

<u>Short description</u>

In this variant conceptual solution, the cell's NPFC is a fixed setpoint for the duration of the control time window. The device droop slopes are determined by means of a distributed negotiation. The FCC at the devices act on measured frequency deviations with a threshold.

<u>Black Box functions</u>

- Cell NPFC Setpoint Informing *(not in scope)*
- Device Droop Slope Determination: variant 4 (Distributed / Negotiation)
- FCC Controlling with deadband
- Frequency Observing
- Power Steering



Note : For the inner (continuous) loop : this is active all the time ; until a new droop is negotiated, it operates based on the previous setting.

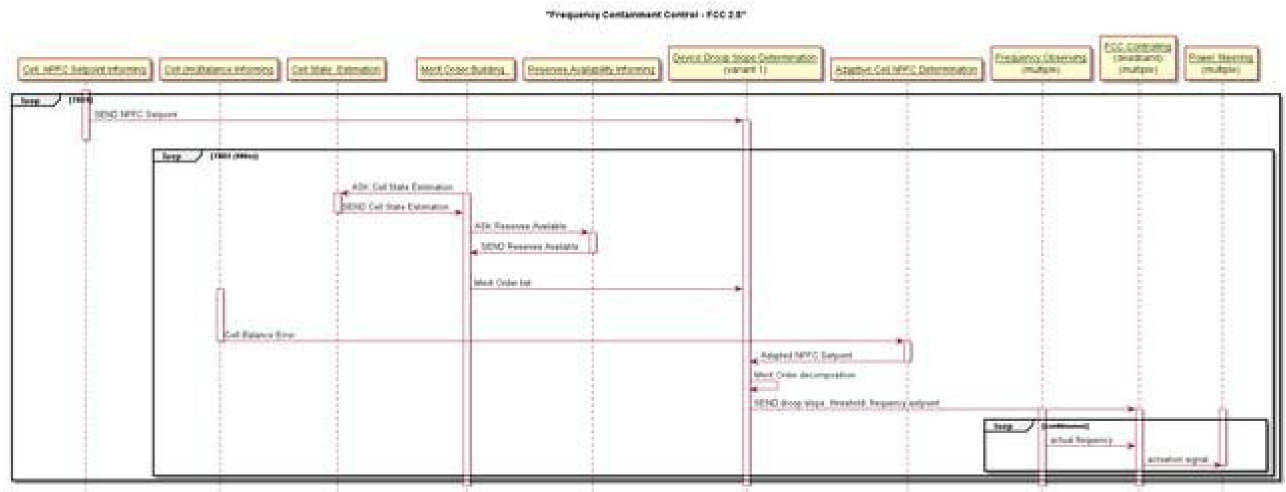
1.5.4 FCC2.5 : FCC with frequency threshold and real-time cell balance error signal

Short description

In this variant conceptual solution, the cell's NPFC is adapted based on the cell's (Im)Balance Error Signal (corrected for the FCC activation) in order to mitigate imbalance causing FCC activations in cells that otherwise are in balance. The FCC at the devices act on measured frequency deviations with a threshold.

Black Box functions

- Cell NPFC Setpoint Informing *(not in scope)*
- Cell (Im)Balance Observing *(not in scope)*
- Cell State Estimation
- Adaptive Cell NPFC Determination
- Device Droop Slope Determination: variant 1 (Central / Merit Order / Direct)
- Reserves Status Informing
- FCC Controlling with deadband
- Frequency Observing
- Power Steering



Note : For the inner (continuous) loop : this is active all the time ; until a new droop is negotiated, it operates based on the previous setting.

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3. Balance Restoration Control

D3.1 formulated objective : Power balance within the cell as well as power exchange with other cells is restored to its scheduled value after activating Balance Restoration Reserves

*Clarification : with 'Power Balance within a cell' is meant its net import/export ; a cell is called in balance if it's net import/export profile corresponds to its setpoint import/export profile. So this control aims at keeping a cell's import/export profile in line with the profile that was given at its T_i. There is **no** requirement that a cell's generation equals its load.*

1.1 Specific control aims: possible variants

- Cell power balance setpoint (single value) **versus** Tie-line powerflow profile setpoints per tie-line (and by definition then also the cell balance is controlled)
- Act on imbalances caused in the cell **versus** act on all imbalances also those caused by other neighbouring cells
- Offset imbalance error signal for FCC and ISC activations **versus** not offsetting the imbalance error signal

Note 1 : Cell Imbalance is defined as a cell's deviation from its setpoint net import/export profile or schedule. This setpoint profile itself is determined in a holistic system wide market clearing process.

Note 2 : Cell Imbalances can be caused :

- *in the cell itself by deviations from forecasts or local incidents*
- *in the cell itself by the activation of reserves by other controls (that were not part of the setpoint schedule, though maybe some machine learning / model predictive control functionality could be applied to offset the centrally determined setpoint profile based on load and generation forecasts : to be discussed)*
- *powerflow deviations that are resulting from imbalances in other – neighbouring – cells (because cells are physically connected)*

Note 3 : In a strict 'solve local problems locally' approach, BRC should only act on imbalances that are caused in the cell itself. While this makes sense for imbalances/deviations caused by local forecast errors or local incidents, this is less clear for deviations caused by reserves activations, where a distinction should be made between reserves activation that address local problems (i.e. voltage), versus reserves activations that address system wide problems (i.e. frequency and inertia). The first category is a must-do and the BRC must take a corrective action that does not work against or undoes the reserves activation. For the second category, the advisable strategy would be to avoid – or at least mitigate – such activations in cells that are in balance and that become imbalanced because of the activation, and concentrate/refocus such system problem triggered activations in cells that are not in balance anyway and thereby contribute to the systemwide problem that causes the activation.

Note 4 : Not only would it be very complicated and expensive to only act on imbalances that are caused in the cell itself (a cell controller would need to know from each individual connection point

whether it is deviating from its forecast and/or whether it activated reserves), but it probably is even better to act on all imbalances as this provides a collaborative approach where neighbouring cells support each other. The especially good thing is that although cells that otherwise would be in balance activate resources, there is a large degree of locality and proportionality in this collaboration, as neighbouring cells would be impacted more that distant cell. This in contrast to a classical control like FCC that acts on a system-wide observable without any locality.
Note 5 : an interesting discussion is how the BRC should act in response to deviations caused by reserves activations by other controls. Should it counter (i.e. undo) such activations giving higher priority to driving the cell to its balance ? Or should it not counter such activations (i.e. correcting the cell balance error signal with an offsetting " $-K.\Delta f$ *" factor which basically mean that BRC will NOT restore a cell's balance but instead maintains an imbalance related to the FCC activations) ? The most sound approach is to not counter local activations that address local problems (voltage related) but drive towards full cell balance restoration (i.e. not to offset the imbalance error signal with the imbalancing effect of these local problem correcting activations). But activations that result from controls addressing global/system problems (frequency and inertia related) should be countered (e.g. no "* $-K.\Delta f$ *" factor) or these controls themselves should be made smarter in a way that avoids or limits their activation in cells that otherwise would be in balance in order for them to not cause lasting cell imbalances ; this then requires some form of coordination to ensure that at all times sufficient system supporting reserves are activated*

	Cell or tie-line focused		All imbalances		Offset error signal for FCC and ISC activations		
	Cell[1]	Tie-line[2]	Yes[3]	No[4]	Yes[5]	No[6]	
$[Cell_{SP} - \sum P_{tieLine\_Act}]$	X		X			X	CA1
	X			X		X	CA2
$[\sum P_{tieLine\_SP} - \sum P_{tieLine\_Act}]$		X	X			X	CA3
		X		X		X	CA4
$[Cell_{SP} - \sum P_{tieLine\_Act}] - K.\Delta f$	X		X		X		CA5
	X			X	X		CA6
$[\sum P_{tieLine\_SP} - \sum P_{tieLine\_Act}]$		X	X		X		CA7
		X		X	X		CA8

1 *only care about cell's total import/export based on aggregated tie-line powerflows without caring about individual tie-line powerflows.*

2 *care about deviation of individual tie-line setpoint versus actual powerflows. Obviously it is not possible to direct reserves activation to one single specific tie-line as each activation will have an impact on all tie-lines. But that does not exclude that through other tie-lines acting in turn on such activations, they collaboratively and dynamically will drive towards the desired cell setpoint as other tie-line controllers will push back ? Further discussion and consensus building on whether this is worth exploring is needed (taking into account anticipated technological advancements making it possible to direct powerflows in an active manner).*

3 *acting on all imbalances strictly speaking violates the 'solve local problems locally' concept, yet there IS an aspect of locality as neighbouring cells will sense adverse effects more strongly than distant cells that may not sense them at all. Besides being a practical approach, it has the additional benefit that it provides collaborative corrective actions where neighbouring cells help each other (similarly as FCC, yet more locality as the powerflow impact is local and proportional as opposed to frequency which is a system wide observable).*

4 *this strict 'solve local problems locally' variant, only acting on imbalances caused in the cell itself, is likely a hypothetical case, as it requires detailed and up-to-date information of all connection points in the cell.*

5 *this 'offset error signal for FCC and ISC activations' variant will NOT restore the cell's balance and therefore is not deemed an acceptable variant.*

6 *this 'do not offset error signal for FCC and ISC activations' variant will restore the cell's balance but at the same time counters/undoes the FCC and ISC activations which may lead to an insufficient amount of such activations. Therefore we will propose an FCC and ISC that is aware of a cell's imbalance situation and avoids/limits activations in cells that are in balance (yet this requires special measures to ensure that at system levels till sufficient reserves are activated ; so either FCC/ISC activation responsibility is handed over to other cells, or maybe more pragmatically a surplus of activations is initiated so that if a number of them are blocked, still a sufficient amount will be activated).*

1.2 Architectural options for BRC specific control aims

Note : We focus here on the most basic architectural variants that directly impact the technicality of the solutions (observables and controls). Additional variants that focus more on the practical implementation e.g. related to the scalability of the solution – e.g. aggregators that aggregate multiple reserves providing resources – are not considered here as these would lead to unnecessary complexity and an explosion of the variant space. Such specific variants – where relevant – will be added in the subsequent whiteboxing and implementation phase.

1.2.1 Control Loop Architecture : two variants

- Decentral Monitor/Central Controller (CA1, CA2 but also CA3, CA4) versus Decentral Monitor/Decentral Controller (CA3, CA4)

1.2.2 Controller type : three variants

- PI-controller type (the control signal is a direct or indirect power activation signal) versus policy controller type (the control signal is a policy) versus MPC controller type

1.2.3 Control Signal Provision Type : two variants

- Direct Merit Order based versus Indirect Bid based.

Note : merit orders are assumed to be location and cell state aware and ensure congestion avoiding activations ; bids are assumed to be not location and cell state aware and congestions might happen so functionality is needed to detect congestions, adjust the activations based on this, and inform the BRC so that corrective measures can be taken ; this will be detailed during whiteboxing.

1.3 BRC variants (36 variants)

For CA1 (x=1), CA2 (x=2)

Variant	Control Loop Architecture*	Controller type			Control Signal Provision type	
	Decentr.Mon, Central Contr.	PI	MPC	Policy	Direct	Indirect
BRCx.1	**X**	**X**			**X**	
BRCx.2	**X**	**X**				**X**
BRCx.3	**X**		**X**		**X**	
BRCx.4	X		X			X
BRCx.5	**X**			**X**	**X**	
BRCx.6	X			X		X

For the CA1 and CA2 options/specific objectives, by definition the monitor is decentralized (measure all tie-lines) and the controller is central (collect information from all tie-lines to compare the sum against the cell setpoint). In this document we describe the base case scenario that for instance assumes that the merit order takes into account cell state and location of the devices and thereby the merit order can be assumed to be congestion free. Later on we can add special (exception) case scenarios where a congestion still occurs in which case additional functionality is needed to deal with this.
Note : Policy controller types always result in a direct control signal provision.

For CA3 (for x = 3) and CA4 (for x = 4)

Variant	Control Loop Architecture*		Controller type			Control Signal Provision type	
	Decentr.Mon, Central Contr.	Decentr.Mon, Decentral Contr.	PI	MPC	Policy	Direct	Indirect
BRCx.1	**X**		**X**			**X**	
BRCx.2	X		X				X

BRCx.3	X			X		X	
BRCx.4	X			X			X
BRCx.5	X				X	X	
BRCx.6	X				X		X
BRCx.7		**X**	**X**			**X**	
BRCx.8		X	X				X
BRCx.9		X		X		X	
BRCx.10		X		X			X
BRCx.11		X			X	X	
BRCx.12		X			X		X

**For the CA3 and CA4 options/specific objectives, the controller can be centralized (as for CA1 and CA2, but now the dispatching decision can take into account individual tie-line deviations), or it can be decentralized where each tie-line has its own local controller.*
Note : Policy controller types and MPC controller types need further explanation and discussion. Current assumption is that Policy controller types always result in a direct control signal provision (being the policy).

Preliminary proposed selection of variants that will be elaborated further (whiteboxing/design, implementation and testing in combination with the other controls) : this selection may be narrowed further after discussion with the other UC writing teams:

- The variants related to CA2 and CA4 (only activate based on imbalance caused in the cell itself) is probably unrealistic as it requires continuous information from all connection points, so only variants related to CA1 and CA3 will be selected.
- Select mainly PI-controller type variants as the most basic controller type option to assess the practicality and impact of the other architectural variances. For CA1 (cell setpoint) compare the direct (merit order based) and indirect (bid based) control signal provision types (**BRC1.1** and **BRC 1.2**). For CA3 (tie-line setpoints) focus on the comparison between the central controller variant versus the decentral controller variant for the most basic (direct / merit order based) control signal provision type (**BRC3.1** and **BRC3.7**).
- Select one as simple as possible variant (i.e. direct merit order based) for both a policy based controller type (**BRC1.3**) and a MPC controller type(**BRC1.5**)

1.4 Black Box functions needed

1.4.1 Cell State Estimation function

This cell central function builds a forecasted estimate of the cell's grid state (bus voltages and line flows) to be used by the Merit Order Building function.

- Input : grid topology with connection points, bus voltages (dynamic measurement) and line flows (dynamic measurement), other TBD information
- What : forecast grid state for the next TBD time window.

- Output : Estimated bus voltages and line flows for the next TBD time window (a time vector with values for each bus)

Note : further discussion is needed on whether the forecasted estimate is based on bus measurements only, or whether additional information - and which one - is needed (e.g. updated weather forecasts) e.g. to update forecasted deviations in connection points or on the cell as a whole.

Note : further discussion is needed on what machine-learning technology could be applied for such cell state estimation.

Note : further discussion is needed on whether this is only done once in each control time window, or whether this is repeated regularly.

1.4.2 Reserves Status Informing function

Each reserves providing resource (and the aggregator) has a function that provides up-to-date information on its reserves providing capabilities for the next time window as well as associated cost.

- Input : none (local information)
- What : Determine how much and what type of reserves can be provided
- Output : a description of what reserves can be provided for what cost

Note : Strictly speaking we need here variants depending on what output information is given for what purpose (e.g. for merit order building versus bid clearing versus …). This additional level of detail will be added during the next whiteboxing phase.

1.4.3 Merit Order Building function

This cell central function build a merit order based on the information received by the Cell State Estimation function and the Reserves Status Informing function. The merit order not only takes into account the cost of an activation, but as well the cell state estimation and the location of the reserves providing resource in the cell, so that (normally) all activations can be done in a grid secure manner.

- Input : cell state estimation, reserves information
- What : Determines a location and cell state aware merit order list
- Output : an ordered list of reserves to be activated (which one and how much and/or according to what profile)

Note : we assume that the Merit Order Building function also takes into account location information (e.g. through some sort of registry : see OS4ES) so that a congestion avoiding merit order can be calculated. In the next steps we could decide to elaborate additional (exceptional) scenarios where this is not the case i.e. no location information is used (but then also the cell state is not needed ?) or even though this is used, congestions can still occur.

1.4.4 Tie-line Powerflow Observing function

At each tie-line there is a powerflow observation device that monitors in realtime the tie-line powerflows and transform this into a tie-line observable.

- Input : tie-line powerflow measurements
- What : Determine the powerflow observable per tieline
- Output : powerflow observable per tie-line

1.4.5 Cell (Im)balance Observing function (for CA1 and CA3)

This cell central function collects and aggregates the tie-line observables and transforms this into a cell balance error signal.

- Input : tie-line powerflow observables, cell setpoint
- What : Determine the cell's balance error
- Output : cell balance error signal

Note : the reason to define this as a separate function instead of including it in the BRC Controller *function,* is that we need this function's output in other controls (e.g. FCC) as well (to make these controls cell balance status aware).

1.4.6 Tie-line (Im)balance Observing function (for CA3)

At each tie-line there is a function that compares the tie-line setpoint with the actual tie-line powerflow and based on this calculates a tie-line error signal.

- Input : tie-line powerflow observables, tie-line setpoint
- What : Determine the tie-line error signal
- Output : tie-line error signal

1.4.7 BRC Controller function

This function determines the control signal based on the error signal

Variant 1 : cell-central (CA1), PI, direct
- Input : cell balance error signal, merit order list
- What : select from merit order list
- Output : activation commands from the merit order list

Variant 2 : cell-central (CA1), PI, indirect
- Input : cell balance error signal, bids
- What : calculate incentive signal to be sent to all devices
- Output : incentive signal that is broadcasted to all devices

Variant 3 : cell-central (CA1), Policy, direct
- Input : cell state estimation, reserves availability
- What : calculate policies for all devices
- Output : policy for each device

Variant 4 : cell-central (CA3), PI, direct
- Input : cell balance error signal, tie-line error signals, merit order list
- What : select from merit order list
- Output : activation commands from the merit order list

Variant 5 : cell-central (CA3), PI, indirect
- Input : cell balance error signal, tie-line error signals, bids
- What : calculate incentive signal to be sent to all devices
- Output : incentive signal that is broadcasted to all devices

Variant 6 : cell-central (CA3), Policy, direct
- Input : cell state estimation, reserves availability
- What : calculate policies for all devices
- Output : policy for each device

Variant 7 : tie-line (CA3), direct
- Input : tie-line error signal, merit order list
- What : select from merit order list
- Output : activation commands from the merit order list

Variant 8 : tie-line (CA3), indirect
- Input : tie-line error signal, bids
- What : calculate incentive signal to be sent to all devices
- Output : incentive signal that is broadcasted to all devices

Variant 9 : tie-line (CA3), Policy, direct
- Input : cell state estimation, reserves availability of the local device
- What : calculate policies for the local device
- Output : policy for the local device

Note (for all variants) : We assume that the BRC controller function takes care of – if needed – determining a profile or plan of activations so that BSC does not need to be concerned with 'reserves replacement' functionality.

So if some replacement would be needed, we assume that this already is taken care of by the BRC's activation (schedule). To be discussed if and how MPC and/or machine learning can be used to anticipate on expected future activations ?

Note : For the tie-line variants : would each tie-line controller then have its own set of resources, or would they share a common set through some sort of registry ? How would they avoid conflicts and prioritize in case of shared resources ?

1.4.8 Power Steering function

Each reserves providing resource has a function that increases/decreases its power generation/consumption as requested.

- Input : power activation signal
- What : increases/decreases power generation/consumption as requested
- Output : increased/decreased power generation/consumption

1.5 Selection Description (incl. MSCs)

1.5.1 BRC 1.1

Short description

In this variant conceptual solution, The Cell Imbalance is defined as a deviation of the **cells's total import/export** (sum over all its tie-lines powerflows) from a cell setpoint that is determined centrally by a market clearing function (out of scope for the control functionality : we can assume that there is a setpoint received as a starting point T_i for the real-time control to begin). And this setpoint is a profile that indicates the cell's total cleared import/export per time step : timestep and horizon TBD (based on experiments : what should be the time resolution to achieve a stable control versus what is feasible given communication delays etc ? what is the time horizon : 15' as of today or could it be longer ? …). This means that in this variant we will have for each tie-line a monitor for the tie-line powerflow, and a central controller that compares the sum of all these tie-line powerflows against the cell's setpoint.

The controller acts on **ANY imbalance** that it observes, irrespective of whether the imbalance is caused in the cell itself or whether it is caused by its neighbouring cell (collateral effect because cells are connected).

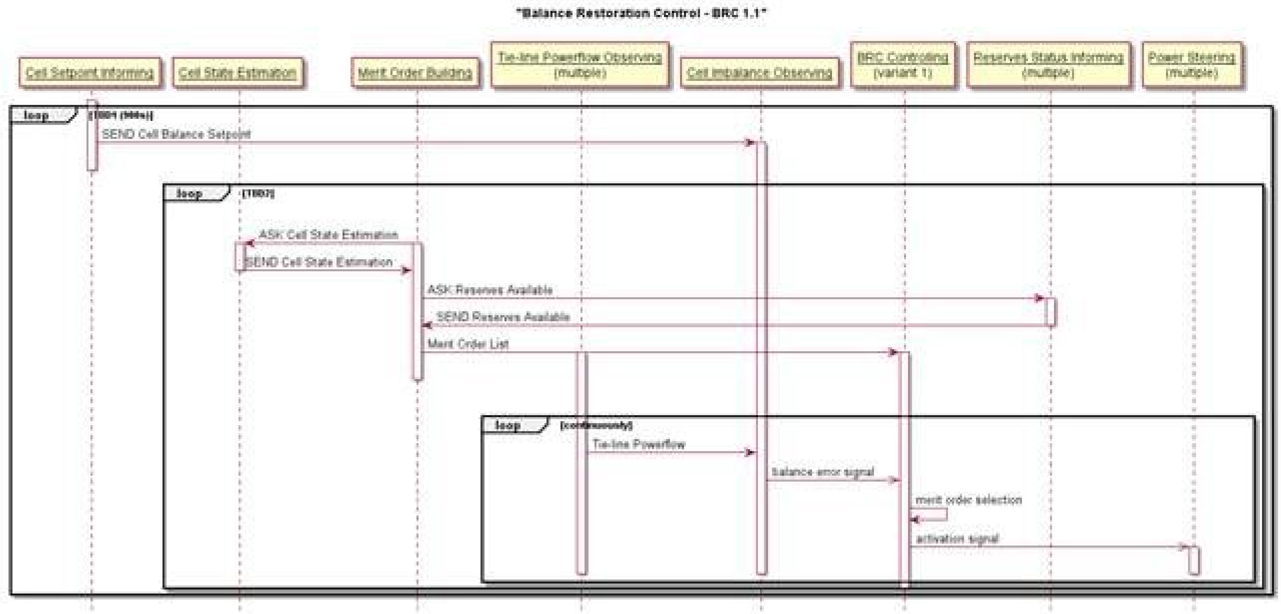
As controller paradigm in this variant is a – classical – PI controller.

As control signal provision type, this solution uses a direct dispatching of resources based on a merit order list that takes into account up-to-date flex availability of the flex providing resources (including their activation cost and location), and up-to-date cell state information so that the merit order based activation decisions are guaranteed to be grid-secure / congestion free.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Cell State Estimation
- Reserves Status Informing
- Merit Order Building
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing
- BRC Controlling (Variant 1)

- Power Steering



1.5.2 BRC 1.2

Short description

In this variant conceptual solution, The Cell Imbalance is defined as a deviation of the **cells's total import/export** (sum over all its tie-lines) from a cell setpoint that is determined centrally by a market clearing function (out of scope for the control functionality : we can assume that there is a setpoint received as a starting point for the real-time control to begin). And this setpoint is a single schedule that indicates the cell's total import/export per time step : timestep and horizon TBD (based on experiments : what should be the time resolution to achieve a stable control versus what is feasible given communication delayes etc ? what is the time horizon : 15' as of today or could it be longer ? …). Based on this we will have for each tie-line a monitor for the tie-line powerflow, and a central controller that compares the sum of all these tie-line powerflows against the cel's setpoint.

The controller acts on **ANY imbalance** that it observes, irrespective of whether the imbalance is caused in the cell itself or whether it is caused by its neigbouring cell (collateral effect because cells are connected).

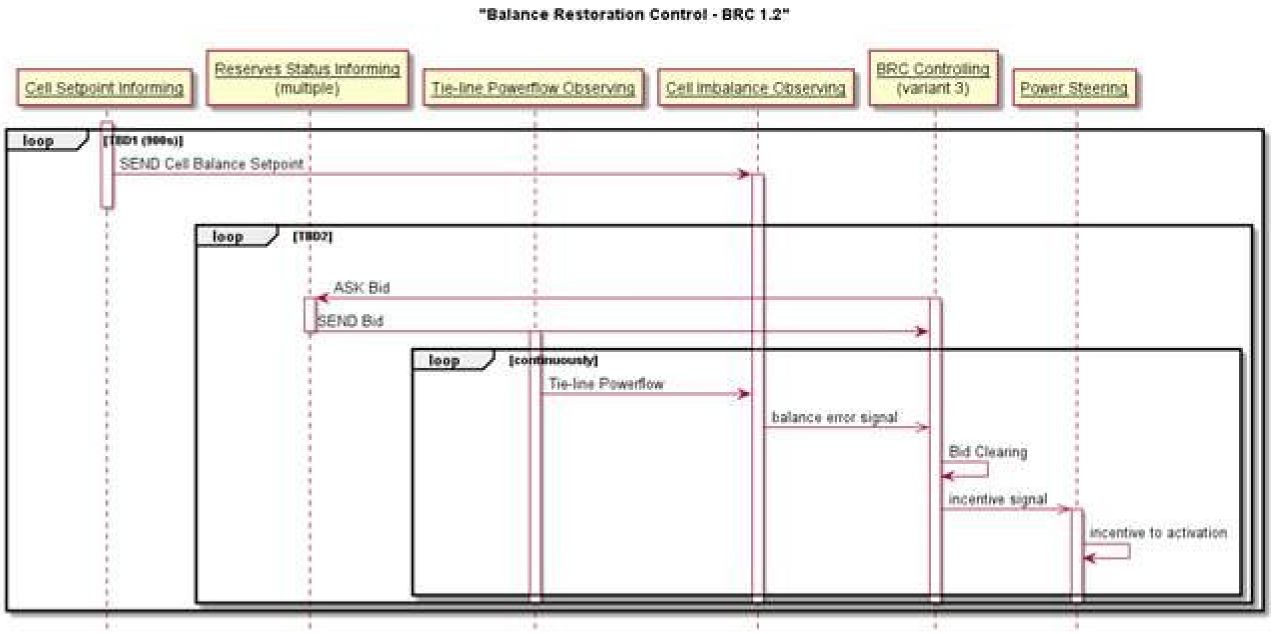
As controller paradigm, we use a – classical – PI controller.

As control signal provision type, this solution uses an indirect dispatching of resources based on incentive signals that are determined based on received bids.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Reserves Status Informing
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing

- BRC Controlling (Variant 2)
- Power Steering



1.5.3 BRC 3.1

<u>Short description</u>

In this variant conceptual solution, The Cell Imbalance is defined as a deviation of the **<u>cells's</u>** **<u>total</u>** **<u>import/export</u>** (sum over all its tie-lines) from a cell setpoint that is determined centrally by a market clearing function (out of scope for the control functionality : we can assume that there is a setpoint received as a starting point for the real-time control to begin). And this setpoint is a single schedule that indicates the cell's total import/export per time step : timestep and horizon TBD (based on experiments : what should be the time resolution to achieve a stable control versus what is feasible given communication delays etc ? what is the time horizon : 15' as of today or could it be longer ? …). Based on this we will have for each tie-line a monitor for the tie-line powerflow, and a central controller that compares the sum of all these tie-line powerflows against the cel's setpoint.

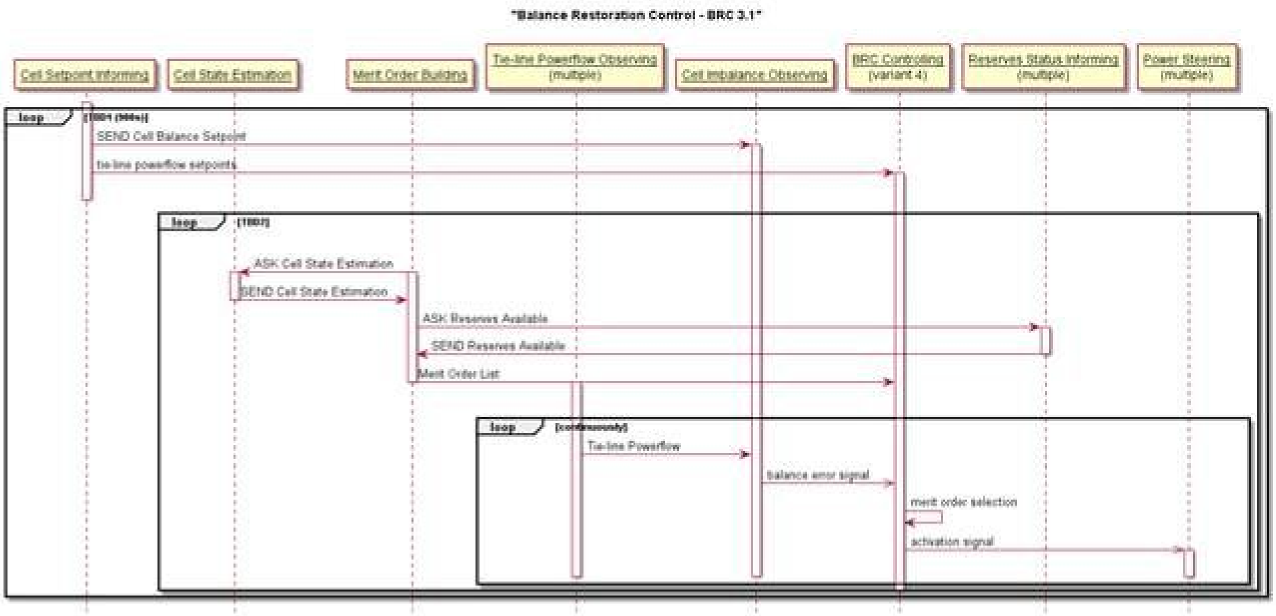
The controller acts on **<u>ANY</u>** **<u>imbalance</u>** that it observes, irrespective of whether the imbalance is caused in the cell itself or whether it is caused by its neigbouring cell (collateral effect because cells are connected).

As controller paradigm, we use a – classical – PI controller.

As control signal provision type, this solution uses a direct dispatching of resources based on a merit order list that takes into account up-to-date flex availability of the flex providing resources and their activation cost and location, and up-to-date cell state information to take into account for the merit order building in such a way that grid-secure activations (no congestions) are guaranteed. **For the activation decisions, this variant takes as well takes into account individual tie-line actual versus setpoint powerflows.**

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Cell State Estimation
- Reserves Status Informing
- Merit Order Building
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing
- BRC Controlling (Variant 4)
- Power Steering



1.5.4 BRC 3.7

Short description

In this variant conceptual solution, The Cell Imbalance is defined as a sum of the deviations of the **individual tie-line powerflow deviations** compared to the individual tie-line powerflow setpoints.

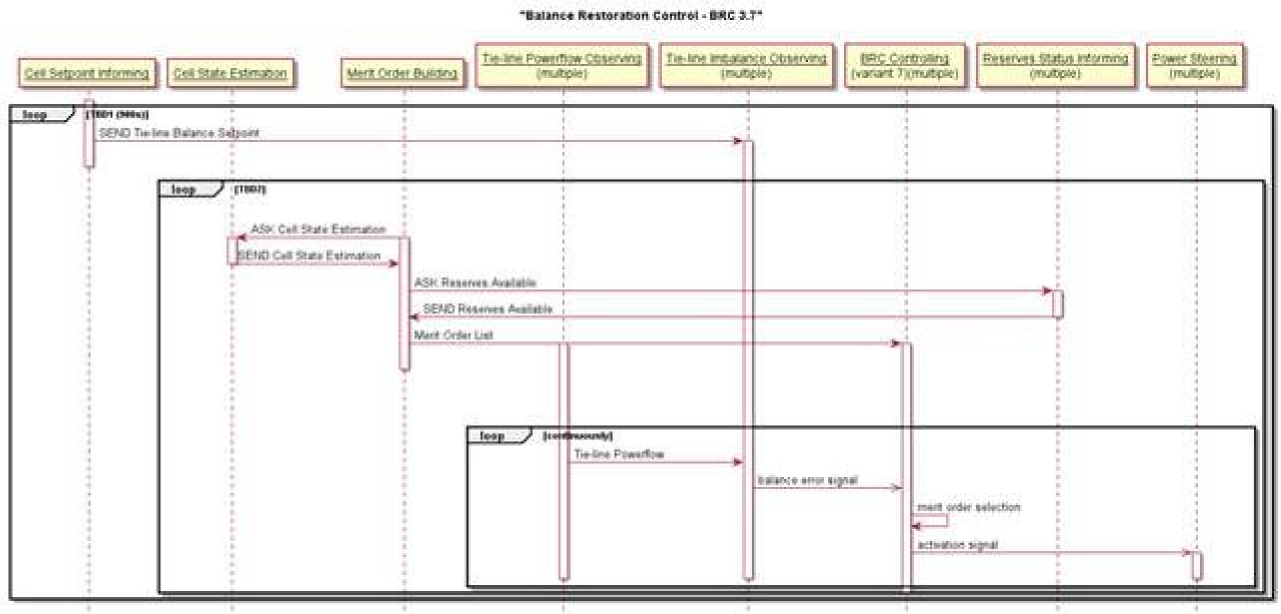
The controller acts on **ANY imbalance** that it observes, irrespective of whether the imbalance is caused in the cell itself or whether it is caused by its neigbouring cell (collateral effect because cells are connected).

As controller paradigm, we use a – classical – PI controller.

As control signal provision type, this solution uses a direct dispatching of resources based on a merit order list that takes into account up-to-date flex availability of the flex providing resources and their activation cost and location, and up-to-date cell state information to take into account for the merit order building in such a way that grid-secure activations (no congestions) are guaranteed.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Cell State Estimation
- Reserves Status Informing
- Merit Order Building
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing
- BRC Controlling (Variant 7)
- Power Steering



1.5.5 BRC 1.3

Short description

In this variant conceptual solution, The Cell Imbalance is defined as a deviation of the **cells's total import/export** (sum over all its tie-lines) from a cell setpoint that is determined centrally by a market clearing function (out of scope for the control functionality : we can assume that there is a setpoint received as a starting point for the real-time control to begin). And this setpoint is a single schedule that indicates the cell's total import/export per time step : timestep and horizon TBD (based on experiments : what should be the time resolution to achieve a stable control versus what is feasible given communication delayes etc ? what is the time horizon : 15' as of today or could it be longer ? …). Based on this we will have for each tie-line a monitor for the tie-line powerflow, and a central controller that compares the sum of all these tie-line powerflows against the cel's setpoint.

The controller acts on **ANY imbalance** that it observes, irrespective of whether the imbalance is caused in the cell itself or whether it is caused by its neigbouring cell (collateral effect because cells are connected).

As controller paradigm, we use a MPC controller.

As control signal provision type, this solution uses a direct dispatching of resources.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Cell State Estimation
- Reserves Status Informing
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing
- BRC Controlling (Variant x)
- Power Steering

1.5.6 BRC 1.5

Short description

In this variant conceptual solution, The Cell Imbalance is defined as a deviation of the **cells's total import/export** (sum over all its tie-lines) from a cell setpoint that is determined centrally by a market clearing function (out of scope for the control functionality : we can assume that there is a setpoint received as a starting point for the real-time control to begin). And this setpoint is a single schedule that indicates the cell's total import/export per time step : timestep and horizon TBD (based on experiments : what should be the time resolution to achieve a stable control versus what is feasible given communication delays etc ? what is the time horizon : 15' as of today or could it be longer ? …). Based on this we will have for each tie-line a monitor for the tie-line powerflow, and a central controller that compares the sum of all these tie-line powerflows against the cel's setpoint.

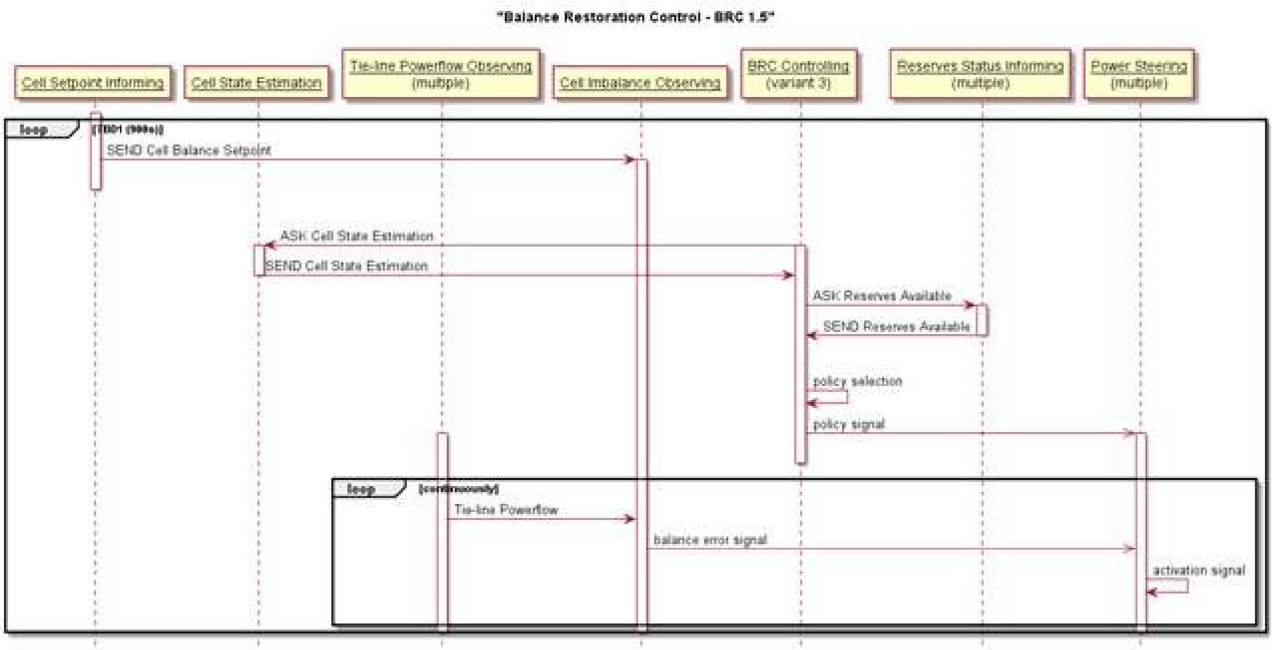
The controller acts on **ANY imbalance** that it observes, irrespective of whether the imbalance is caused in the cell itself (e.g. a cell local forecast error, or an optional FCC-caused activation) or whether it is caused by its neighbouring cell (collateral effect because cells are connected).

As controller paradigm, we use a Policy controller.

As control signal provision type, this solution uses a direct dispatching of resources.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- Cell State Estimation
- Reserves Status Informing
- Tie-line Powerflow Observing
- Cell (Im)Balance Observing
- BRC Controlling (Variant 3)
- Power Steering


"Balance Restoration Control - BRC 1.5"
Cell Setpoint Informing
Cell State Estimation
Tie-line Powerflow Observing (multiple)
Cell Imbalance Observing
BRC Controlling (variant 3)
Reserves Status Informing (multiple)
Power Steering (multiple)
loop
SEND Cell Balance Setpoint
ASK Cell State Estimation
SEND Cell State Estimation
ASK Reserves Available
SEND Reserves Available
policy selection
policy signal
loop
Tie-line Powerflow
balance error signal
activation signal

4. Balance Steering Control

D3.1 formulated objective(s) :

1. ***Secure Cell's balance by selecting appropriate setpoint for balance (and consequently tie-lines flows) taking into account imbalance netting (proactive use based on forecast or reactive after replacing BRC reserves[CC1])***
2. ***Successfully replace BRC reserves by tertiary BSC flexibility resources.***
3. ***Real-time optimise of the activated resources portfolio in terms or efficiency (or cost).***

Reformulated Objective(s) :

1. ***Optimize (minimize) the amount of balancing reserves activations by leveraging imbalance netting between neighbouring cells in a way that an identical system balancing effect is achieved ; this will impact (= determine) a new cell balance setpoint (hence as well new tie-line powerflow setpoints)***
2. ***Ensure that the new – adjusted – tie-line powerflow setpoints are grid secure***

Note: The current proposal is to restrict the BSC functionality to reserves activation optimization/minimization by leveraging imbalance netting between neighbouring cells, and remove the earlier proposed replacement functionality (for cost, speed of activation, duration of activation). The rationale for this is that we expect in future, unlike today, that (BRC and FCC) reserves will be provided mainly by fast and no-fuel (cost) based resources (like flex loads or storage) which removes the need for a staged approach (fast and expensive è slower but cheaper). On the other hand, such new resource classes are energy bound which puts a limit on how long they can be activated, and a schedule of activations where resources take over from other resources may be needed. For now we assume that this scheduling can be taken into account by the BRC merit order selection algorithm but this needs some further discussion (time needed versus time available based on vision related to frequency control). The final decision on this will be taken in the technical workshop Feb 4-5th 2016, and re-evaluated later based on the implementation and testing activities. [CC2]

Note: the interaction modalities and options between BRC and BSC are subject to further technical discussions and analysis. Specifically, we want to avoid BRC activations that are undone later by BSC.[CC3]

1.1 Specific control aims : possible variants

- CA1: the new cell balance setpoints resulting in a reduced reserves activation amount between two adjacent cells contribute equally to the system balance restoration.
- CA 2 : the new tie-line powerflow setpoint between two neighbouring cells is still within the tie-line's secure boundaries.

Note : both of these two CAs must be fulfilled at the same time : they are complementary.

For each pair of cells : minimize the amount of reserves activations ($\sum \Delta Gi + \sum \Delta Li$) with two constraints: 1. $(\sum(Gi + \Delta Gi) + \sum(Li + \Delta Li))full\,restoration = (\sum(Gi + \Delta Gi) + \sum(Li + \Delta Li))BSC\,optimized$ 2. $P_{tie} <= P_{tie\_max}$	CA1 & CA2

Note : as a further sophistication, the optimization could look not at the amount of activations (in amount of power correction), but at the associated cost. Or even other objectives like maximizing future reserves providing capacity of e.g. energy constrained resources, etc.. [CC5]

1.2 Architectural options for BSC specific control aims

Note : We focus here on the most basic architectural variants that directly impact the technicality of the solutions (observables and controls). Additional variants that focus more on the practical implementation e.g. related to the scalability of the solution – e.g. aggregators that aggregate multiple reserves providing resources – are not considered here as these would lead to unnecessary complexity and an explosion of the variant space. Such specific variants – where relevant – will be added in the subsequent whiteboxing and implementation phase.

1.2.1 Control Loop Architecture

- Central Monitor / Central Controller

1.2.2 Controller Paradigm

- 'Classic' optimization (MILP, …) versus Policy based

1.2.3 Mode of operation

- De-activate (resources activated by BRC) versus Pre-empt activation by BRC

1.2.4 Control Signal Provision type

- Direct Merit Order based versus Indirect Bid based

Note : This is only relevant when the BRC controller optimizes for cost instead of power. It then probably makes most sense that it uses the merit order list that was built and used by BRC for deactivation (or avoiding activation) of the most expensive ones, taking into account the effect on the tie-lines though. Alternatively (if de-activating) it could solicit new bids of the activated resources to base its decision on.[CC6]

1.3 BSC variants (8 variants)

All these variants must honour both CA1 and CA2.

Variant	Control Loop Architecture	Controller Paradigm	Mode of Operation	Control Signal Provision type

	entr.Mon, entral Contr.	ILP/ INLP/ A	olicy	e-activate	re-empt	irect, Merit rder based	ndirect, Bid based
SC1.1	X	X		X		X	
SC1.2	X	X		X			X
SC1.3	X	X			X	X	
SC1.4	X	X			X		X
SC1.5	X		X	X		X	
SC1.6	X		X	X			X
SC1.7	X		X		X	X	
SC1.8	X		X		X		X

Preliminary proposed selection of variants that will be elaborated further (whiteboxing/design, implementation and testing in combination with other controls) : this selection may be narrowed further after discussion with the other UC writing teams:

- Focus on Merit Order based Control Signal provision types and 'classical' controller paradigms (MILP, …) as the simplest variants to focus especially on the interactions with the other use cases. For these, compare the de-activation mode of operation (**BSC1.1**) and a pre-empting mode of operation (**BSC1.3**) variants. If time allows, compare this with a pre-empting policy based variant (**BSC1.7**)

1.4 Black-box functions needed

1.4.1 Cell State Estimation function

See BRC description. BSC uses the estimated cell state to forecast the impact of deactivation or pre-empting actions to ensure that these do not cause grid problems in the cell, and especially to ensure that the tie-line constraints are not violated.

1.4.2 Cell (Im)balance Observing function

See BRC description. BSC uses this Cell Balance Error signal to engage with neighbouring cells to negotiate new setpoints that minimize balance restoration activations (cost).

1.4.3 Setpoint Adjusting function

This cell central function communicates the own cell's imbalance state with its neighbouring cells and learns about their respective imbalances. Based on this it proposes (negotiates) a new setpoint that fulfil the stated specific control aims.

- Input : cell state information (incl. tie-line constraints), cell balance error signal, BRC merit order list
- What : determine new cell balance setpoint
- Output : new balance setpoint

Note : multiple variants can be identified for this function (e.g. related to pre-emption versus de-activation, optimization algorithm, negotiation approach with neighbours, e.g. iterative or one go, one neighbour at the time – and according to which prioritization scheme – or all concurrently, etc… These are key topics that will be discussed at the technical workshop 4-5th February 2016.

1.4.4 Forecasting function

This cell central determines the imbalance forecast which information is needed for the BSC setpoint adjustment function (esp. the pre-empting variants).

- Input : Data of consumption, production, flexibility, prices and weather information
- What : Estimate if and what type of imbalance is forecast in the very short term. Inform BSC of the imminent imbalance.
- Output : Type and amount of imminent imbalance(s)[CC8]

1.5 Selection Description (incl. MSCs)

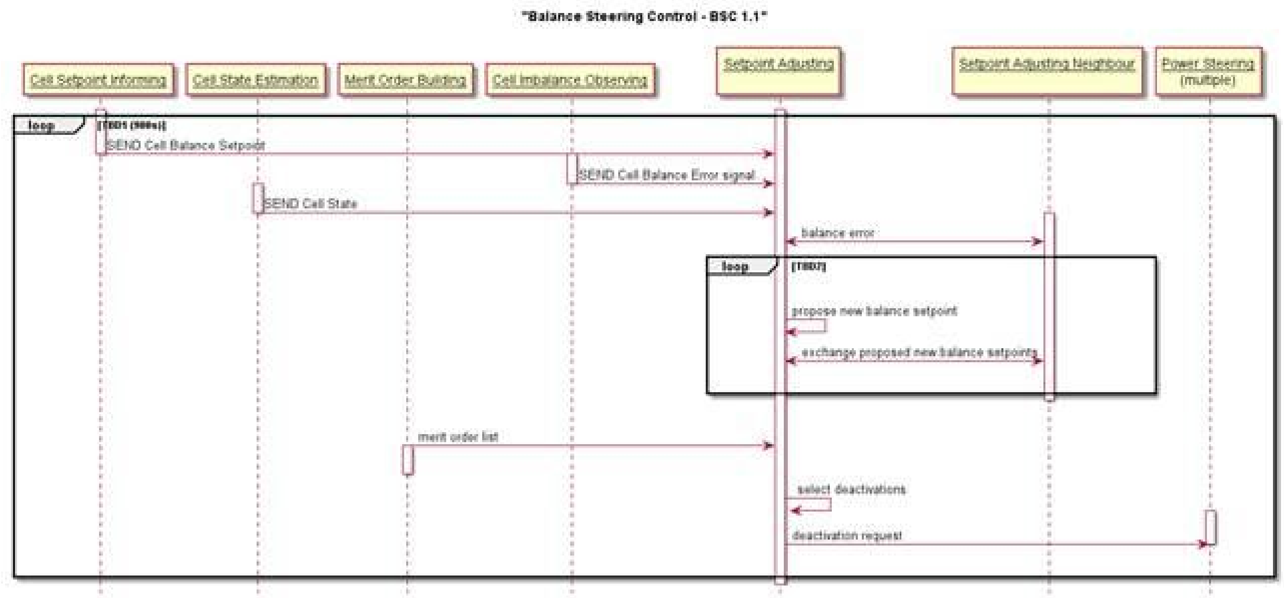
1.5.1 BCS 1.1

Short description

In this variant conceptual solution, the BSC controller will de-activate resources again that were activated by the BRC controller. It will first determine how much resources can be de-activated in a coordinated manner with its neighbouring cells without jeopardizing the stated specific control aims. Next it will determine which resources to de-activate to ensure this is done in a grid secure and cost optimal manner. For this, the same merit order list that was used by BRC to decide on activations is used.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- *Merit Order Building (not in scope)*
- *Cell (Im)Balance Observing (not in scope)*
- *Cell State Estimation (not in scope)*
- Tie-line Powerflow Observing
- Setpoint Adjusting
- Forecasting
- Power Steering



1.5.2 BCS 1.3

Short description

In this variant conceptual solution, the BSC controller will pre-empt BRC resource activations before they are activated by the BRC controller. It will first forecast how much resources can be de-activated in a coordinated manner with its neighbouring cells without jeopardizing the stated specific control aims. Next it will determine which resources to de-activate to ensure this is done in a grid secure and cost optimal manner. This will change the merit order selection that will be used by BRC to activate resources.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- *Merit Order Building (not in scope)*
- *Cell (Im)Balance Observing (not in scope)*
- *Cell State Estimation (not in scope)*
- Tie-line Powerflow Observing
- Setpoint Adjusting
- Power Steering

1.5.3 BCS 1.7

Short description

In this variant conceptual solution, the BSC controller will pre-empt BRC resource activations before they are activated by the BRC controller. It will use policies to forecast how much and which resources can be de-activated in a coordinated manner with its neighbouring cells without jeopardizing the stated specific control aims. This will change the merit order selection that will be used by BRC to activate resources.

Black Box functions

- *Cell Setpoint informing (not in scope)*
- *Merit Order Building (not in scope)*
- *Cell (Im)Balance Observing (not in scope)*
- *Cell State Estimation (not in scope)*
- Tie-line Powerflow Observing
- Setpoint Adjusting
- Power Steering

5. Primary Voltage Control

Primary Voltage Control in the Web-of-Cell concept would not be substantially different from the current PVC except that at LV levels active instead of reactive power activations would be required to drive and maintain a node at its setpoint.

6. Post-Primary Voltage Control

D3.1 formulated Objective : The objective of the PPVC is to provide an optimal and local voltage control for future electrical grids. PPVC will restore the voltage in the nodes to the set-point values, optimizing the reactive power flows in the system, and operating in present SVC time frames.

Reformulated Objective(s) :

1. *Determine V setpoints and deadbands for active nodes (PVC nodes with AVR – droop - functionality) and V setpoints for passive nodes (without AVR functionality, like Tap Changers or capacitor banks) within the regulatory defined safe bands that minimizes the risk of voltages drifting outside the safe band, while minimizing reactive powerflows and activation cost.*

Note: a setpoint recalculation is done either periodically to minimize reactive powerflows (pro-active PPVC), or when a node voltage drifts too much from the setpoint even if it is still within the safe band (pro-active PPVC ; requires a deadband next to a setpoint), or when the voltage drifts outside the safe band (corrective PPVC : typically a large sudden incident that could not be contained by the local / nearby PVC and required a collaborative corrective action by multiple nodes). So we distinguish between a constant safe band (determined by regulation) versus a dynamic node specific deadband which is determined by the PPVC controller

Note : for the pro-active trigger based PPVC, either the deadbands are kept by the cell central controller and the nodes regularly send measured voltages, or the nodes know their deadbands and use this to do the checking themselves and only send a voltage as a trigger when the measured voltage is outside the deadband.

Note: the optimal setpoint calculating OPF algorithm (balancing between reactive powerflow optimization and robust voltage setpoints that don't trigger a new setpoint calculation and/or OLTC switching too often) must take into account the tie-line powerflows at the cell boundaries as a constraint. This algorithm is trading off optimality against robustness and activation cost … you do not want an extremely optimized powerflow that results in voltage setpoints that are so sensitive/critical/touchy that new setpoints must be calculated too often. Besides minimizing powerflows and activation costs (of power activations needed to drive nodes to their new setpoint as well as to maintain that setpoint), other – secondary - objectives could be taken into account like minimizing amount of tap changes etc.

1.1 Specific control aims : possible variants

1. Calculate V setpoints and deadbands that not only are in the regulatory defined safe band, but as well are 'robust' in the sense that they do not need to be recalculated too often.
2. Calculate V setpoints that optimize powerflows (optimize is not necessarily 'minimize' as you need some trade-off with the 'robustness' control aim)

These two control aims are complementary control aims i.e. both must be fulfilled at the same time.

Safe and robust voltage for all nodes	CA1

Optimal powerflow (resulting in minimal losses)	CA2

1.2 Architectural options for PPVC specific control aims

Note : We focus here on the most basic architectural variants that directly impact the technicality of the solutions (observables and controls). Additional variants that focus more on the practical implementation e.g. related to the scalability of the solution – e.g. aggregators that aggregate multiple reserves providing resources – are not considered here as these would lead to unnecessary complexity and an explosion of the variant space. Such specific variants – where relevant – will be added in the subsequent whiteboxing and implementation phase.

1.2.1 Control Loop Architecture

- Decentral monitor/Central controller.

Note : the decentral monitors are the nodes that send their voltage (either continuously e.g. every x seconds, or only when a node voltage drifts beyond the setpoint ; these are different variants as they influence the information that is sent between the functions and the location of the functions e.g. deadband checking is decentralized at the nodes versus done by the cell central PPVC controller).

Note : the cell central controller collects the voltage measurements from the nodes and combines this with other information (like cell state) to calculate new setpoints and deadbands using an OPF algorithm. This OPF algorithm must find the optimal balance between safe and robust voltage settings on the one hand, and optimizing on the other hand.

1.2.2 OPF algorithm

- Multiple variants for the OPF checking in combination with the optimization strategy (linear/non-linear programming, evolutionary, genetic, ….) can be defined. The most sensible variants will be discussed and decided at a technical workshop 4-5th February 2016.

1.3 PPVC variants (TBD)

1.4 Black-box functions needed

1.4.1 Voltage Phasors Calculation function

Each PPVC node (can be either a measurement only node or a PVC node with AVR functionality or a PPVC node without AVR like OLTC or capacitor bank) has a function that a function that determines the voltage phasor at the node.

- Input : Voltage waveforms
- What : Calculation of the RMS voltage and the phase
- Output : Voltage phasor at cell nodes

1.4.2 Load Forecasting function : only for proactive variants

Each node has a function that predicts the future electrical load in a long term horizon (15 min ?)

- Input: Historic load values, other factors (temperature, humidity, holidays/working days…)
- What : Determine the load profile for a future time interval
- Output : Load forecast

1.4.3 **Generation Forecasting** function : only for proactive variants

Each node has a function that predicts the future generation of intermittent (variable+uncertain) energy sources.

- Input: Available resource (wind, solar…), temperature, system location, historical data, specifications of the generator…
- What : Determine the generation profile for a future time interval
- Output : Power forecast

1.4.4 **Cell state estimation** function

It calculates the estimated state of the cell according to the information provided by the measurement and monitoring system and the subsequent observables' calculation. This process can be accomplished for the present time or for a 15-min horizon, depending in the operation mode of the PPVC.

- Input: Characteristics of the network elements, grid topology, network model, measurements/observables
- What : Estimated grid state (present an in a 15-min horizon)
- Output : Generation, active and reactive power flows, active and reactive loads, bus voltages

1.4.5 **Merit-order building** function

It builds a merit order based on the Flexibility Resource/PPVC resource provider information concerning the availability of resources, the generation cost and the physical location of the resources. This way, the cell operator will be able to select those more appropriate (if possible, the cheaper ones) to participate in the PPVC provision.

- Input: Availability signal, generation cost, location
- What: Determine a list of ordered reserves to be activated for the PPVC provision
- Output: Establishment of what resources are going to be activated and how much energy are going to produce.

1.4.6 **PPVC controlling** function

Compare the observables (the voltage magnitude) with the optimal voltage set-points in order to calculate the voltage error signal to trigger the PPVC resources availability function.

- Input : voltage set-points in the cell nodes, voltage magnitude
- What : Compare the set-points with the current values to determine the voltage error signal
- Output: voltage error/activation signal for the PPVC resources availability function.

1.4.7 **PPVC Reserves Status informing** function

The Flexibility Resource or the PPVC Resource Provider (if the resources are aggregated) inform about the availability (the "state" of the resource) to the Cell Operator, as well as it associated cost, in order to include the information for determining the merit-order.

- Input : state of the resource and estimated evolution
- What : Determine how much and what type of reserves can be provided
- Output : a description of what reserves can be provided and the generation costs

1.4.8 Set-point providing function (OPF)

This cell central function determines the node's setpoints (and deadbands) using an OPF algorithms : e.g. set-points in the generation units (or the positions of the OLTC) to optimize the system operation according to several objectives, such as the minimization of losses or the maximization of the grid security.

- Input: Generators' parameters (power limits, connection point data, cost curve), transmission line parameters and transformers parameters (impedances, voltage, ratings, connection point data), load data, stability limits, reserves margins, renewable energy forecasts.
- What: from the input data and the merit-order information, provides the best solution for the generation dispatch.
- Output: generators set-points to serve the load and meet the security requirements

1.5 Selection Description (incl. MSCs)

To be completed based on technical workshop (4-5th February 2016) outcome.

Project No. 609687

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ELECTRA

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

WP 6

Control schemes for the use of Flexibility

Deliverable 6.1

Functional specification of the control functions for the control of flexibility across the different control boundaries

<Annex: Technical description of Main Use Cases>

20/12/2015

Index

List of figures and tables

Tables

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1. Prerequisites

The High-level Use Cases of the ELECTRA project have been defined in Deliverable D3.1, and are listed in table 1:

Table 1: 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, a technical description is provided in the following paragraphs. The technical descriptions outline the technical background and motivation for the breakdown into the detailed use cases and the requirements linking each controller to the overall Web-of-Cells concept and architecture.

Each technical description provides:

- Motivation and concise goals for the overall use case
- A breakdown structure of the use case into sub-systems corresponding to the control topology levels and association of the overall control aim with the physical "system input variable"
- A definition of interactions and required information exchange across sub-systems (i.e. across control topology levels)
- An identification of time scales associated with the operation of each sub-system (control time scale)
- Selection of observables required (and provided) by each level
- A description of the function of the controller operating at each level, where alternative controller realization options are pointed out
- The stakeholders who will be responsible for the controller and associated resources
- Remarks on physical limitations of use cases (e.g. frequency control in a DC cell is meaningless; the concept would have to be adapted)

Wherever possible, the control aims and observables are directly related to previously identified control triples.

1.1. Composing Use Cases from Control Functions

The Use Case composition is to be done in two stages:

1. Technical description, and based on this:
2. Use Case description

1.2. Content completeness checklist for Technical UC descriptions

Table 2: Basic definitions (see also D5.1 "Terminologies"):

Term	Definition
Control Time Scale (CTS)	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
Control Topology Level (CTL)	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

Table 3: Content completeness checklist for Technical UC Descriptions

Criterion	Explanation
High-Level use case control aim	• Is the overall aim of the high-level use case clear (i.e. independent of topology levels breakdown)? Is the final system input variable identified clearly?
CTL breakdown of High level use case	• Is it clear how the overarching control aim is broken down into objectives at each topology level? • Are the control objectives identified per level?
Controller function definition, distribution of control actions, and alternative controllers	• Are the control functions for each level (CTL) clearly defined? If relevant, are alternative control realizations identified? How are the control functions divided and distributed? Are the alternatives clearly distinguished?
Interactions across topology levels and information exchange across cells	• Is the overall flow of handling information clear? Is it specified which information is exchanged between systems at different control topology levels?
Coordination of time scales	• Is the information exchanged provided and with the related time scale (CTS1-3)? • Are continuous data flows distinguished from time-, or event-triggered information exchange?
Time sequence/phases	• How are the actions of different controllers/coordination algorithms sequenced w.r.t. time? • E.g. if resources are activated that have previously been allocated as reserves, or if the activation/coordination scheme includes allocation, what time sequence and coordination horizons are expected?
Observables	• Are Observables identified (and meaningfully distinguished for each relevant level)? • Different controllers (for the same control aim) might need different observables - for each controller, are the meaningful observables defined? • Flexibility resources also need to be observed in many cases, is the relevant observable specified?

2. Technical description - Use Case Inertia Response Power Control (B1.IRPC)

2.1. Impact of Low Rotational Inertia

Traditionally, electricity generation is based on rotating synchronous machines which participate in frequency control via their kinetic energy, providing or absorbing active power from the grid continuously , thereby slowing down the rate of change of frequency. Thus frequency dynamics are slow, which also offers the time to respond after instantaneous large power imbalances (e.g. loss of a large generator or tie line). The high share of renewable energy sources, notably inverter-connected, reduces the available rotational inertia within the power system, with implications for frequency dynamics and power system stability. Lower inertia in the power system implies that the frequency dynamics become faster, making frequency control more challenging. New techniques have been implemented to emulate the rotational inertia, for example deploying virtual synchronous generators using external energy resources (e.g. battery energy storage systems).[1]

In the past, power system operation was based on the assumption that a fixed amount of inertia is present in the system, since electricity generation was mainly provided by conventional synchronous generators. In the future power system, with a high share of weather-dependent resources, this assumption is not valid anymore because the ratio between rotating and static generators will vary over time. For example, electricity generation of wind plants will be expected to be replaced by conventional power plants during windless periods, and vice-versa during windy periods.

2.2. Simplified model:

Following a frequency deviation, synchronous generators will exchange power with the grid, resulting in a change of the kinetic energy E_{kin} stored in the rotating mass of the generator:

$$E_{kin} = \frac{1}{2} J (2\pi f_m)^2 \qquad (1)$$

where J is the moment of inertia of the synchronous generator and f_m is the rotating frequency of the machine.

Rotating generators are characterized by an inertia constant H measured in seconds which denotes the amount of time where the generator is able to produce electrical energy equal to the kinetic energy of its mass at rated power. The inertia constant H for a synchronous machine is defined by:

$$H = \frac{E_{kin}}{S_B} = \frac{J(2\pi f_m)^2}{2\, S_B} \qquad (2)$$

where S_B is the rated power of the generator.

The swing equation can be written as:

$$\dot{f_m} = \frac{f_0}{2HS_B}(p_m - p_e) \qquad (3)$$

where p_m is the mechanical power supplied to the generator, p_e the electric power demand and f_0 is the reference frequency.

2.3. Aggregated swing equation:

Modelling an interconnected power system with n generators, j loads and l tie lines leads to the aggregated swing equation:

$$\dot{f_m} = \frac{f_0}{2HS_B}(P_m - P_{load} - P_{loss}) \qquad (4)$$

$$S_B = \sum_{i=1}^{n} S_{Bi} \qquad H = \frac{\sum_{i=1}^{n} H_i S_{Bi}}{S_B}$$

$$P_m = \sum_{i=1}^{n} P_{mi} \qquad P_{load} = \sum_{i=1}^{j} P_{loadi} \qquad P_{loss} = \sum_{i=1}^{l} P_{lossi}$$

where $P_m$is the total mechanical power of the generators, P_{load} the total system load of the interconnected power system, P_{loss} the total losses of the transmission lines, H the aggregated inertia of all the system.

Figure 1 presents the frequency behavior after the loss of a generation unit. As shown the rate of change of frequency, $\frac{df}{dt}$, (ROCOF) is higher in case of lower inertia H in the system.

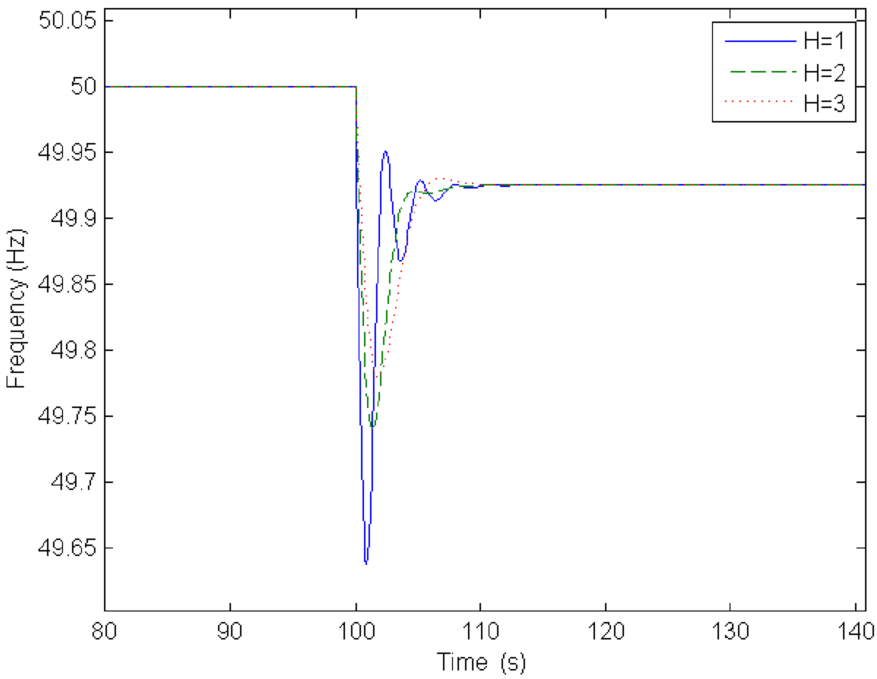

Figure 1: Frequency behavior after the loss of a generation unit

As can be observed from (3) and (4), to calculate the requested inertia H to maintain a certain $\frac{\Delta f}{\Delta t}$, $(P_m - P_e)$ needs to be defined.

2.4. Objectives in ELECTRA Context

Following the frequency control architecture as defined in the ELECTRA project (i.e. Use Cases) [2], inertia response power control should be activated during a large disturbance and well before frequency containment control. The control objectives of inertia response power control are:

- The limitation of rate of change of frequency, $\frac{df}{dt}$, to a maximum allowed value and thus maintaining a certain level of frequency stability, during contingencies
- Limiting the frequency deviations during normal operation to a specified range ($f_{min} < f < f_{max}$)
- Supporting frequency containment control (FCC) until FCC is fully activated

2.5. The Control Layers for IRPC

The inertia response power control (IRPC) is achieved by means of a layered control structure.

Table 4: Layered control structure for IRPC

Control Topology Level	Control function
CTL-3	Specifying a required amount of inertia Ji from each cell i, which is coordinated among the cell operators in a synchronous region, based on the frequency control objectives: $\frac{d\omega}{dt} = \frac{(p_m - p_e)}{\omega \sum_1^n J_i}$
CTL-2	Maintaining a fixed amount of (physical or virtual) inertia Ji provided from each cell (operator)
CTL-1	Providing inertia from aggregated units
CTL-0	Providing inertia from individual units

Having a synchronous region where different cells are connected, the required amount of inertia requested from each cell is defined at synchronous region level. Each cell operator should be able to provide the requested amount of inertia. Since the system virtual inertia is based mainly on energy resources outside the considered cell, the cell operator could provide the requested inertia using energy resources as virtual inertia or physical inertia from neighbour cells following a market-based approach. Afterwards, the individual units able to participate in the inertia control should be able to exchange active power proportional to the ROCOF, therefore behaving as a synchronous machine with a specific amount of inertia.

In case of an isolated cell, operating in island mode, the cell operator becomes the only actor responsible for controlling the cell, limiting the ROCOF, and limiting the frequency deviation. To do so, the cell operator needs to define the required amount of inertia based on its own control objectives, and then maintain a fixed amount of inertia (physical or virtual) within the cell.

As mentioned above, since the ratio between static and rotating generators is changing over time, the cell operator should check on a regular basis if enough inertia response is present in its own cell.

2.6. Composition of Control Triples for IRPC control functions

The steps in Chapter "2.1.7.2. Composition of Control Aims/triples for control functions" are followed. The resulting control triples are listed in the following sub-sections:

2.6.1. Step 1

Main Use Case: B1.IRPC (Balance Control; Inertia Response Power Control)

Deliverable D3.1 Control Objective: "Contain dynamic frequency deviations in normal operation."

2.6.2. Step 2

From the filtered list of control triples in the online spreadsheet "Use Case B1.Inertia Response Control", the following control triples have been selected as building blocks.

Table 5: Control Triples for Inertia Response Power Control

Topology layer	UC.CTL	Control Time Scale	WP5 Control Aim	WP5 Observable	WP5 System Input Signal
CTL_2 Cell level	B1.IRPC.CTL_2	CTS_3 3.Tertiary Level	11-Inertia Steering at Cell level [s]	Actual Cell Inertia time constant [s]	Deployment of inertial response power in a collection of converter interfaced resources [0/1]
CTL_0 Physical device level	B1.IRPC.CTL_0	CTS_0 0.System response	02-Minimise stationary frequency fluctuations [Hz/s]	Actual frequency of node voltage [Hz]	Inertial response power [W]
CTL_0 Physical device level	B1.IRPC.CTL_0	CTS_1 1.Primary Level	08-Inertial Response Power Dynamic Control [s]	Inertial time constant of DER [s]	Inertial response power [W]

2.6.3. Step 3 and Step 4

There are at least two different ways to achieve the control objective:

1. Individual device solution, for many devices
2. Cascaded control solution, for many devices

The control triples and control diagrams of these solutions are shown in the following sub-sections.

2.6.3.1. Individual device solution, for many devices

The control triple of individual device solution, for many devices can be found in Table 6.

Table 6: Control Triple of individual device solution

Topology layer	UC.CTL	Control Time Scale	WP5 Control Aim	WP5 Observable	WP5 System Input Signal
CTL_0 Physical device level	B1.IRPC.CTL_0	CTS_0 0.System response	02-Minimise stationary frequency fluctuations [Hz/s]	Actual frequency of node voltage [Hz]	Inertial response power [W]

Control diagram of individual device solution, for many devices:

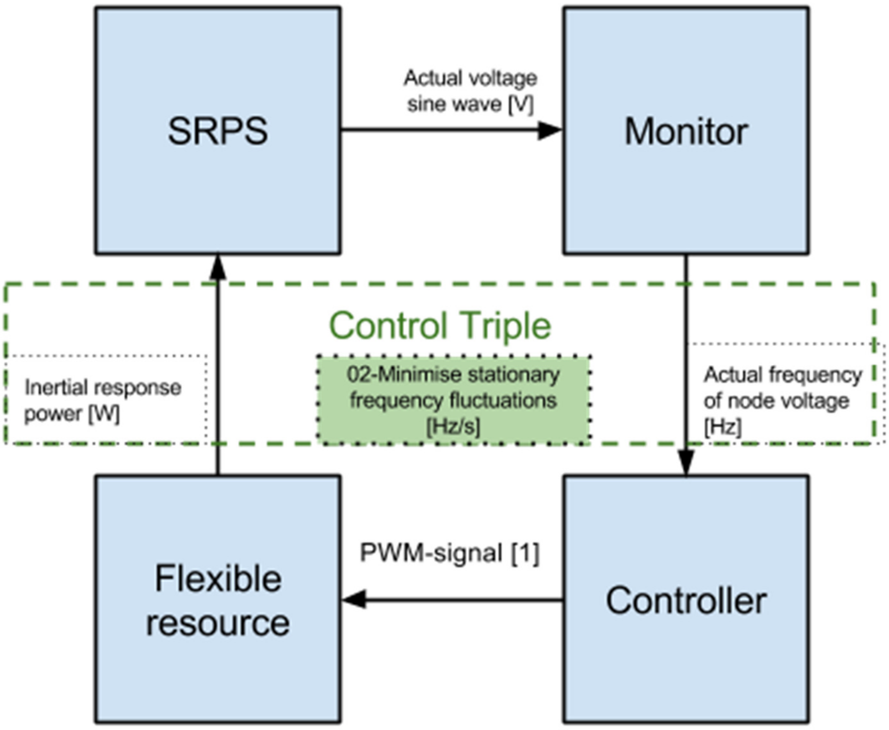

Figure 2: Control diagram of individual device solution

In essence, each individual flexible resource contributes to frequency stabilisation. When this is done for all DER units in the SRPS, then the inertia time constant is kept high enough in order to keep frequency fluctuations below a certain level that is consistent with "normal operation" of the power system.

2.6.3.2. Cascaded Control solution, for many devices

Control triples of cascaded control solution, for many devices are included in Table 7.

Table 7: Control Triples of Cascaded Control solution

Topology layer	UC.CTL	Control Time Scale	WP5 Control Aim	WP5 Observable	WP5 System Input Signal
CTL_2 Cell level	B1.IRPC.CTL_2	CTS_3 3.Tertiary Level	11-Inertia Steering at Cell level [s]	Actual Cell Inertia time constant [s]	Deployment of inertial response power in a collection of converter interfaced resources [0/1]
CTL_0 Physical device level	B1.IRPC.CTL_0	CTS_1 1.Primary Level	08-Inertial Response Power Dynamic Control [s]	Inertial time constant of DER [s]	Inertial response power [W]

Therefore, two control diagrams are needed to describe a cascaded inertia control.

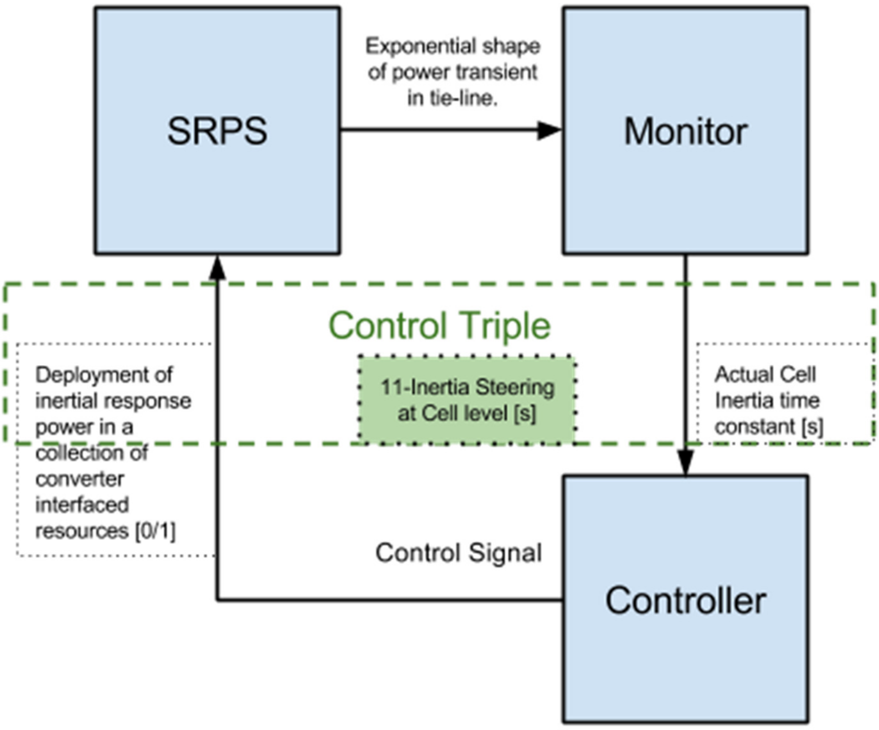

Figure 3: Cascaded Control diagram of DER collection (top layer)

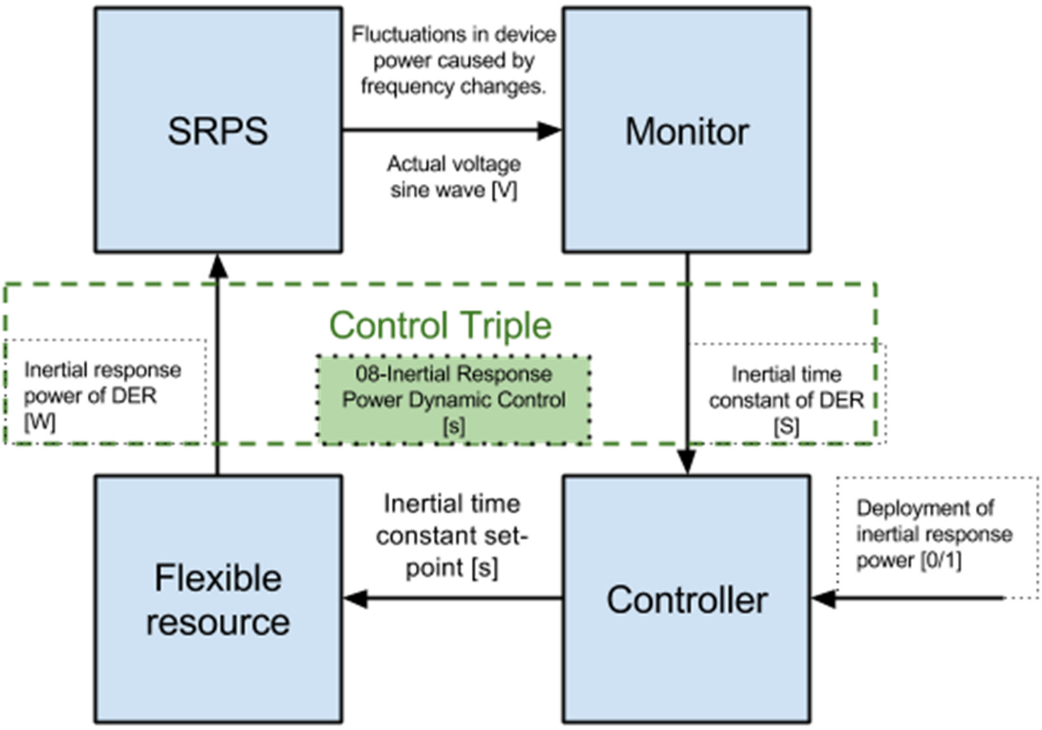

Figure 4: Inertial Response Power Dynamic Control of DER units (bottom layer)

The Controller in figure 4 receives deployment signals from the central controller in the top layer of the cascaded control loop. Along with the “on-off” signal, a set-point for the fraction of the maximum inertial time constant could be transmitted; in fact, there will be many devices deployed in this way by the central Controller when during everyday operation the inertia fraction becomes too low during periods when decentralised resource feed in a substantial amount of generation power, thereby replacing central synchronous generators.

2.7. References

[1] V. Karapanos, P. Kotsampopoulos, and N. Hatziargyriou, “Performance of the linear and binary algorithm of virtual synchronous generators for the emulation of rotational inertia,” Electr. Power Syst. Res., vol. 123, pp. 119–127, 2015.

[2] P. No, “ELECTRA Deliverable D3.1 Specification of Smart Grids high level functional architecture for frequency and voltage control,” 2015.

3. Technical description - Use Case Frequency Containment Control (B2.FCC)

3.1. Background

Frequency Containment Control has the main objective of responding to imbalances that lead to system frequency deviations. It is therefore necessary for the specific control to achieve a prescribed response of power as a function of frequency. In present power systems, this functionality is divided into two main processes: the actual response of generators (and occasionally loads) to frequency deviations, and the regulation of a total system response depending on operating conditions. The main contributors to the former process are synchronous generators via droop characteristics of governors. The aggregated behaviour of the synchronous area with response to frequency changes on the other hand is determined by control area operators by means of the network power frequency characteristic. Both processes are vital for the stable operation of future networks with a diverse portfolio of resources. To this end, because of the gradual reduction of synchronous generators, FCC shall be mainly provided by distributed energy resources, including flexible consumers, with the capability of responding to frequency deviations based on prescribed control functions.

3.2. Objectives in ELECTRA context

Obviously, the main objectives of FCC remain the same regardless of the resources used:

- Response to frequency deviations
- Regulation of network power frequency characteristic

However, in the ELECTRA view of the future power system, there are differences in many respects, such as regarding resources, processes and involved actors. This has some implications with regard to the implementation of the FCC control strategy.Namely synchronous generators will still be capable to provide such service and the regulation of NPFC will be done based on the same premises with the difference that new actors will be involved such as cell (instead of control area) operators. The implementation of FCC to DER requires the use of power-frequency droop control as part of the power converter control that connects the resource to the grid. In contrast with synchronous generators, in which a linear droop response is an operating characteristic required by the grid code, inverter-based resources should implement this as an extra service, so that each individual device participating in FCC can change its power output as a function of frequency. Also, due to the increased flexibility that will be provided by consumers it is also necessary to consider the stepwise response of such loads to frequency changes. The response of loads becomes beneficial especially when there is aggregation and appropriate parameter settings so that a linear, droop-like response can be achieved. This way, a vast amount and diversity of resources can contribute to FCC.

The aggregation of response is not limited to the local response of aggregated resources (such as loads) but can be extended to higher levels, i.e. cells and synchronous area, in order for the resources to be appropriately parameterized and provide a desired overall system characteristic (according to to the selected NPFC value). This can be achieved by determining the availability of reserves through market procurement mechanisms, determination of overall system needs based on daily profiles by cell operators, and regulation of parameters of individual/aggregated resources so that they can respond to frequency changes in the prescribed ways. It is noteworthy that any regulation of NPFC beyond the limits of a synchronous area is by definition meaningless because each synchronous area has different steady-state frequency. Therefore, the highest level of this control (CTL-3) is always confined within a synchronous area. Finally, it should be clarified that the above described approach of NPFC steering (and any other responsive-to-frequency control) does not apply within the domain of DC networks because, obviously, frequency there is not defined. However, to the extent that these parts of the grid are capable of controlling their power flow at their connection to the AC grid point, they can be treated as aggregations of devices which collectively participate in the various frequency control schemes.

3.3. Control Process

The required processes for FCC in order to meet the two objectives of the previous paragraph can be summarised in the following steps:

NPFC objective:

- Determination of operating requirements based on schedules and power profiles. This process is done by operators at synchronous area level.
- Determination of available reserves for FCC provision. This is a market-based mechanism intended to provide Cell Operators with a minimum amount of reserves (Flexible Resources) which can be used for FCC.
- Estimation of individual cells' contribution to the NPFC of the synchronous area based on their production yield. At this step, the actual production of each cell over time is used by the synchronous area operator to estimate the contribution coefficient of each cell to the NPFC.
- Observation and regulation of NPFC at cell level. At this step, each cell (automatically) regulates its NPFC based on measurement of its real NPFC. The control procedure implemented at this stage determines the set of parameters (droop or similar) for the aggregated resources and individual devices.

Frequency response objective:

- Having determined the controller parameters, the FCC controller at aggregated resource or individual device can provide its power modification as a function of frequency, whenever required by the system operating conditions. Therefore, actual frequency is monitored and used as input to the controller signal which, based on the frequency error calculates the power change that the resource should provide. The only differences between aggregated and single devices are the locality of measurement (frequency is locally measurement by devices or centrally by aggregators) and granularity of power (control of individual loads yields more granular step changes in power).

3.4. Control Layers for FCC

The implementation of the previous steps in the whole procedure necessitates the hierarchical organisation of actions/functions. The following table summarises these levels together with the main actions involved.

Table 8: Topology levels and control functions for FCC

Control Topology Level	Control function
CTL-3	Establish NPFC at system level and determine contributions of each cell
CTL-2	• Determine available reserves capacity based on procurement at cell level • Regulate the NPFC contribution of a cell to the overall system characteristic by adjusting the resource's parameters
CTL-1	Respond to frequency deviations by monitoring frequency and centrally controlling individual devices (active power or on/off set points). If aggregated (CTL-1) control is used local controllers (CTL-0) FCC are unnecessary should not be implemented.
CTL-0	Respond to frequency deviations by monitoring frequency locally and controlling device state (active power or on/off set point)

CTL-3: Represents the domain of Web-of-Cells governed by synchronous area operator. This area consists of multiple cells and it is required to maintain a specific NPFC depending on the conditions mentioned in the previous paragraphs. The operator at this level is responsible for identifying the operation limits of the area as well as the coefficients for the contributions of each individual cell below.

CTL-2: The main responsibilities of CTL2 are to ensure specific reserves availability via market procurement and to regulate the reserved resources thereafter in order to meet the requests of the CTL-3 controller. The reason for considering procurement at CTL-2 level is that the required reserves concern only the involved cell and therefore the procurement should refer to local participants (reserve providers). For the regulation of NPFC in real time it is essential that the CTL-2 controller be aware of the actual response via relevant observation of the corresponding NPFC value.

CTL-1: At this level, aggregated resources provide response of power to frequency based on a droop (or similar) control method. To this end, a central frequency observation and control is performed and the output of the controller is a number of signals (active power, on/off state) for individual devices located at CTL-0.

CTL-0: It is possible that one single device participates in FCC at CTL-0. Such an example can be a bulk synchronous generator. The basic difference between CTL-0 and CTL-1 is that in CTL-0 frequency and control is performed locally at device level, a practice currently used in synchronous generators. Also, the CTL-0 implementation may differ in terms of power granularity, something especially evident when the device is a load operating in on/off mode. In this case, the power profile is stepwise rather than linear as in the general droop control case implemented in aggregated or individual resources.

3.5. Composition of Control Triples for FCC control functions

The composition of control triples for FCC follows the methodology described in Section 2.1.7.2.

3.5.1. Step 1

Main Use Case: B2.FCC (Balance Control; Frequency Containment Control)

Control Objective 1 (in case of frequency/imbalance incidents): “React to deviations of absolute frequency value so as to contain any change and stabilise frequency to a steady-state value”

Control Objective 2 (under normal operating state): “Observe and regulate in real time the NPFC within the system area”

3.5.2. Step 2

The table below provides an overview of the detailed control triples needed in order to realise FCC.

Table 9: Control triples for FCC

Control Topology Level	Control Time Scale	Control Aim	WP5 Observable	WP5 System Input Signal
0.Physical (single) Device Level	CTS_1 1.Primary Level	Minimise frequency deviations [Hz]	Frequency [Hz]	Active power of Synchronous Generator [W]
1.Flexible (aggregate) Resource Level	CTS_1 1.Primary Level	Minimise frequency deviations [Hz]	Frequency [Hz]	Active Power of aggregated resources [W]
2.Cell level	CTS_3 3.Tertiary Level	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]
3.Inter-cell level	CTS_3 3.Tertiary Level	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]	Cell Energy production in standard time interval [Ws]	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]
3.Inter-cell level	CTS_3 3.Tertiary Level	Regulation of Network Power Frequency Characteristic (λi) [W/Hz]	Web-of-Cells Energy production in standard time interval [Ws]	Deployment of Power-Frequency droop slope of aggregated resources [W/Hz]

3.5.3. Step 3

The two main objectives present some fundamental implementation differences. Therefore, the deployment of power-frequency response at CTL-0 is a conventional control of a large synchronous generator. CTL-1 is a decentralised control scheme with resource boundaries while the part concerned with NPFC is a cascaded control scheme where outputs of higher-level controllers are used as inputs to lower level controllers. In this respect, the black-box schemes for describing these control objectives are shown below.

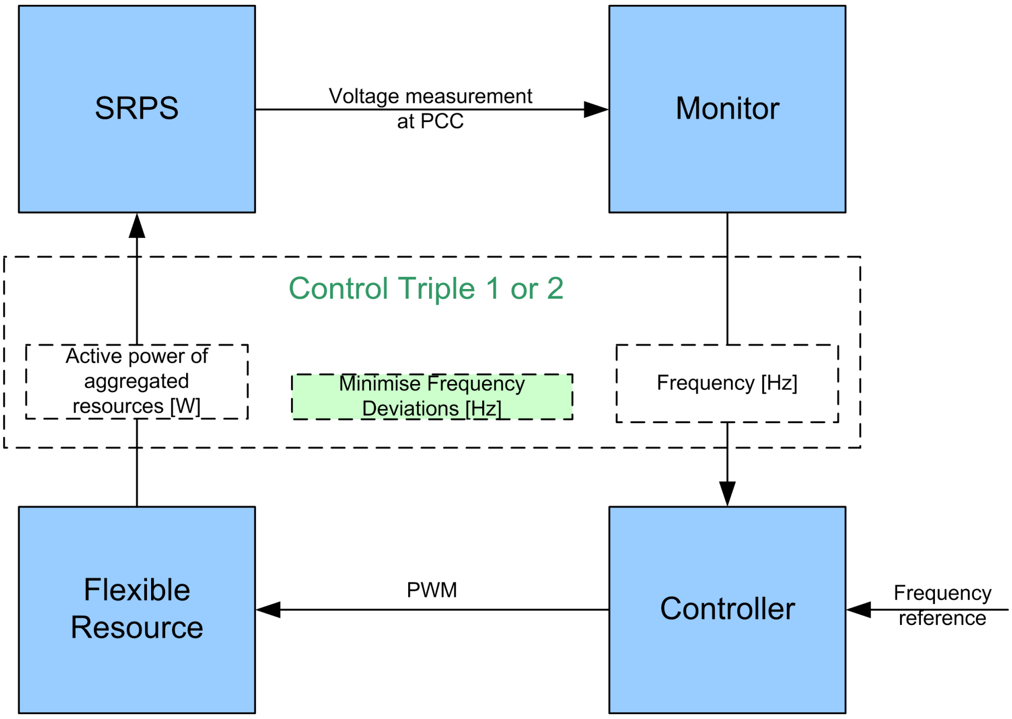

Figure 5: Control Loop diagram for decentralised FCC. This diagram refers to objective 1 (response to frequency deviations) and describes both aggregated resource and single device operation

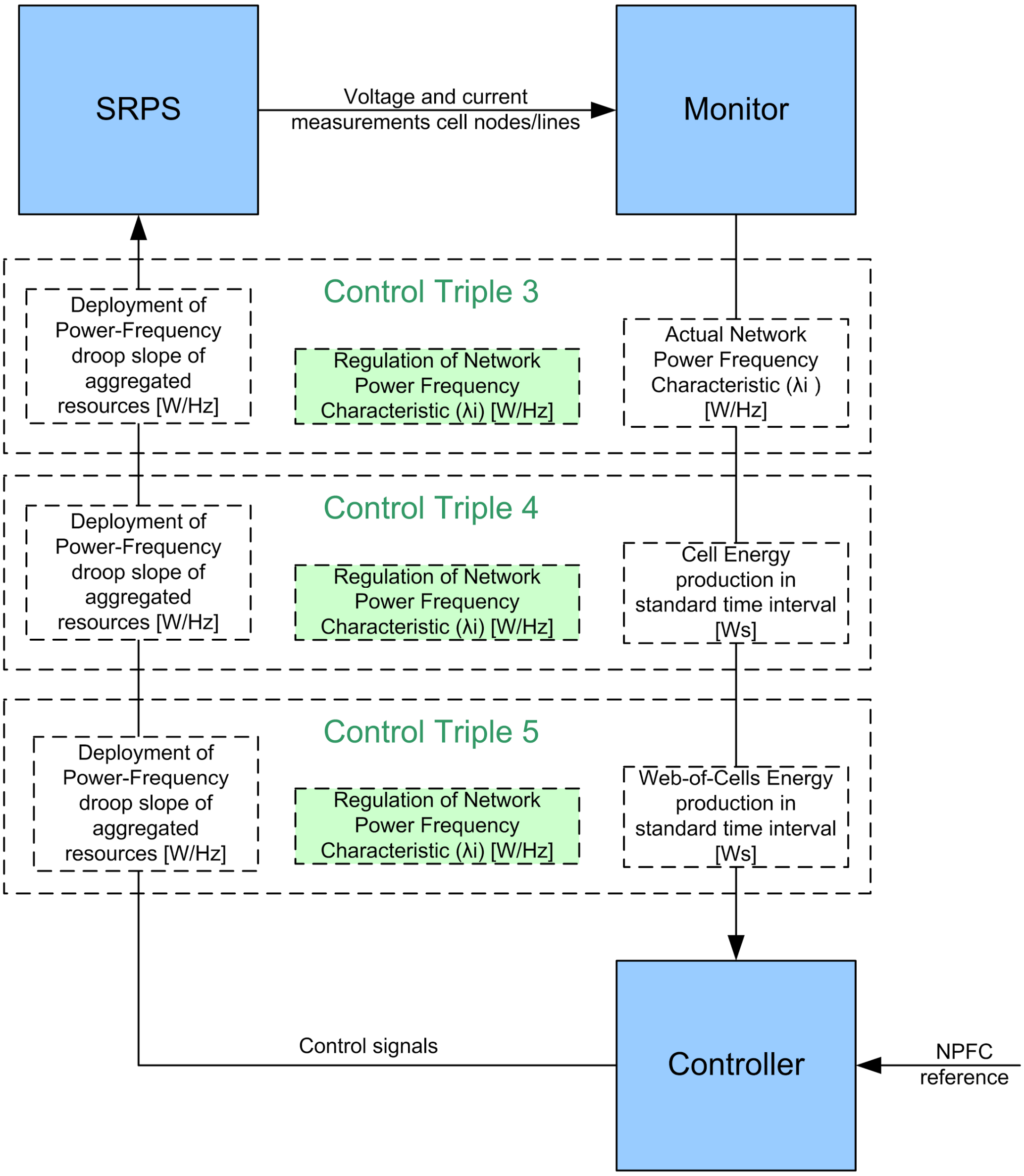

Figure 6: Control Loop diagram for Cascaded FCC. This diagram refers to objective 2 (NPFC regulation)

4. Technical description - Use Case Balance Restoration Control (B3.BRC)

4.1. Background

An imbalance in the planned/predicted load versus production values within a cell causes changes in the power flows across cell borders. The objective of Balance Restoration Control is to restore the cell balance and by doing so, restoring inter-cell load flows to their secure values, and consequently, restoring system frequency to its nominal value.

Based on the difference between scheduled power flow and measured power flow across the cell borders, available BRC reserves within the cell are activated. In traditional frequency restoration control, the restoration reserves providers are mainly large synchronous generators. Because of the decreasing availability of these large generators, different resources with flexibility, such as storage systems, curtailable and/or shiftable load, renewable energy resources are needed to be activated as balance restoration reserves in order to have sufficient reserve capacity available within a cell. It is also necessary that balance restoration reserve capacity can be procured in an economically optimum manner.

The balance of a cell is measured through comparing the scheduled power flows across the cell borders with the measured cell border power flows. In addition to this, power flows resulting from Frequency Containment Control actions are taken into account when calculating the cell imbalance. The amount of balance restoration capacity to activate is determined through a PI-controller with the cell imbalance as input.

Balance Restoration reserves are procured within a cell and ordered in a merit order, based on the costs for reservation as well as the physical state of the network. The physical state of the network is taken into account to avoid that the activation of certain reserves introduces congestions in the network.

When a cell imbalance occurs, the required reserves are activated according to the merit order. Reserves are activated for a maximum period of time, Balance Steering control takes over the balance restoration reserves, after maximum activation time.

Aggregators, aggregating the flexibility from a portfolio of many (different) resources, can act as a restoration reserve provider. In order to comply with a reserve activation request, the aggregators must ensure that the required reserves are activated within the agreed ramp-up time. Therefore, the aggregators have to be aware of the overall flexibility of its combined portfolio, and thus need to know the availability and state of the resources within their portfolio. Resources for restoration reserves are flexible resources in its broadest interpretation: synchronous generators, renewable resources, curtailable load, shiftable load, electricity storage, etc.

4.2. Control process and decomposition in Control Topology Layers

The overall control process of BRC consists of 2 phases: procurement phase, and real-time control phase.
One variant of the procurement phase has been worked out, depicted in Figure 1. Two variants of the real-time control phase are worked out, depicted in Figures 2 and 3.

4.2.1. Procurement Phase

As shown in Figure 7, the balance restoration control procurement process, is a cascaded control. The overall control aim of this procurement phase is the procurement of adequate amount of Balance Restoration Reserves at minimum cost. The control processes happening at each Control Topology level are indicated in the plot.

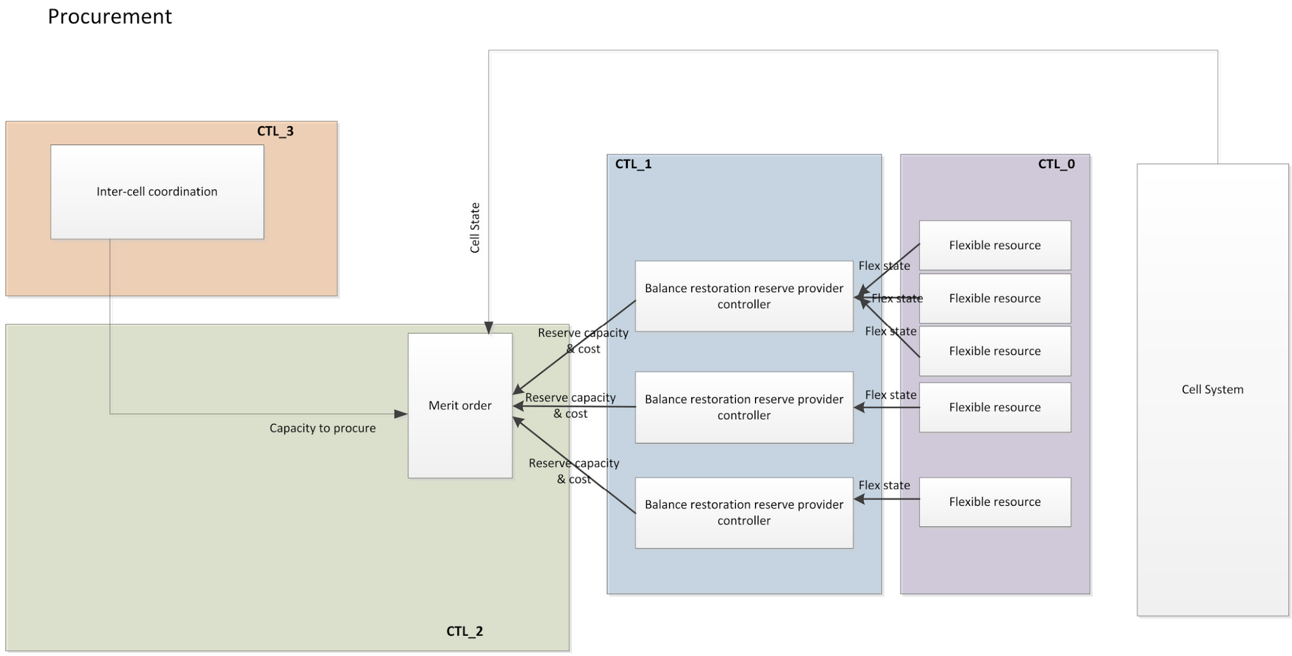

Figure 7: Balance Restoration Control: procurement phase.

4.2.1.1. Control Topology Level 3 (CTL_3)

The control objective of the controller is the definition of the required procurement capacity for each cell. The capacity to procure should be defined for each future timestep. The procurement capacity can be a fixed value over time, but depending on the cell characteristics it can be a changing value over time.

Observables or measurements needed for this CTL3 controller are the characteristics of the cell that enable the calculation of a BRC procurement capacity: probability of imbalance incident, size and timing of imbalance incidents, amount of FCC reserves, …

The output signal of the CTL3 controller is a reserve capacity per timestep, that the cell operator has to procure within his cell.

Timing of the controller: Reserves have to be procured per timestep. Since many market mechanisms operate on a 15-minute timestep, it would be logical to follow a 15-min. timestep base for reserve procurement. To allow the cell operator the time to procure the required capacity, the controller output signal should be available quite some time before T0. (1 hour before).

4.2.1.2. Control Topology Level 2 (CTL_2)

The control objective of the controller at CTL_2 level is the setting up of a so-called ‘merit-order’ of the procured reserves. The merit order indicates which reserves will be activated at a certain measured imbalance. The merit order is set up based on costs of the reserves. The cell system state (or a prediction of the cell system state) can also be taken into account so that the activation of reserves does not induce grid congestion issues.

Observables or inputs for this CTL2 controller are the cell system state, and the reserve capacity bids of every restoration reserve provider willing to bid within the cell. The required capacity to procure, defined by the CTL_3 controller, is also an input for this CTL_2 controller.
The output of the CTL2 controller is a merit order that at least contains the required restoration reserve capacity, at minimal cost. The reserve capacity providers receive a signal to let them know whether or not they are included in the merit order.
Timing of the controller: The merit order should be available at least 15 minutes before possible activation time (t0).

4.2.1.3. Control Topology Level 1 (CTL_1)

The control objective of the controller at CTL_1 level is the definition of reserve capacity bids based on the portfolio of the reserve resource of the restoration reserve provider. Reserve capacity bids indicate how much reserves can be offered at what timestep and at what cost.
Observables or inputs for this CTL_1 controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.
The output of the CTL_1 controller is a restoration capacity bid, indicate how much reserves can be offered at what timestep and at what cost.
Timing of the controller: The capacity bids should be available at least 1 hour before possible activation time (T0), to allow the system operator enough time to set up the reserve merit order.

4.2.1.4. Control Topology Level 0 (CTL_0)

The control objective of the controller at CTL_0 level is the definition of the flexibility state of the flexible resource. This flexibility state must indicate what the options are for the resource to be controlled so that inherent resource-constraints are not violated.
Observables or inputs for this CTL_0 controller are dependend on the resource.
The output of the CTL_0 controller is an indication of the flexibility state of the flexible resource.
Timing of the controller: The flexibility state information should at least be available 1 hour before possible activation.

4.2.2. Real Time Control Phase

Two variants of the real-control phase are worked out below, both are depicted in figures 8 and 9.
As shown in figures 8 and 9, the real-time control phase of balance restoration control is a cascaded control.
The overall control aim of this real-time control is the activation of an adequate amount of Balance Restoration Reserves at minimum cost, without violating any grid constraints. The required reserve capacity should be activated within a timescale of 15 minutes.
The control processes happening at each Control Topology level are indicated in both figures 8 and 9.

4.2.2.1. Variant 1

Real-time control phase

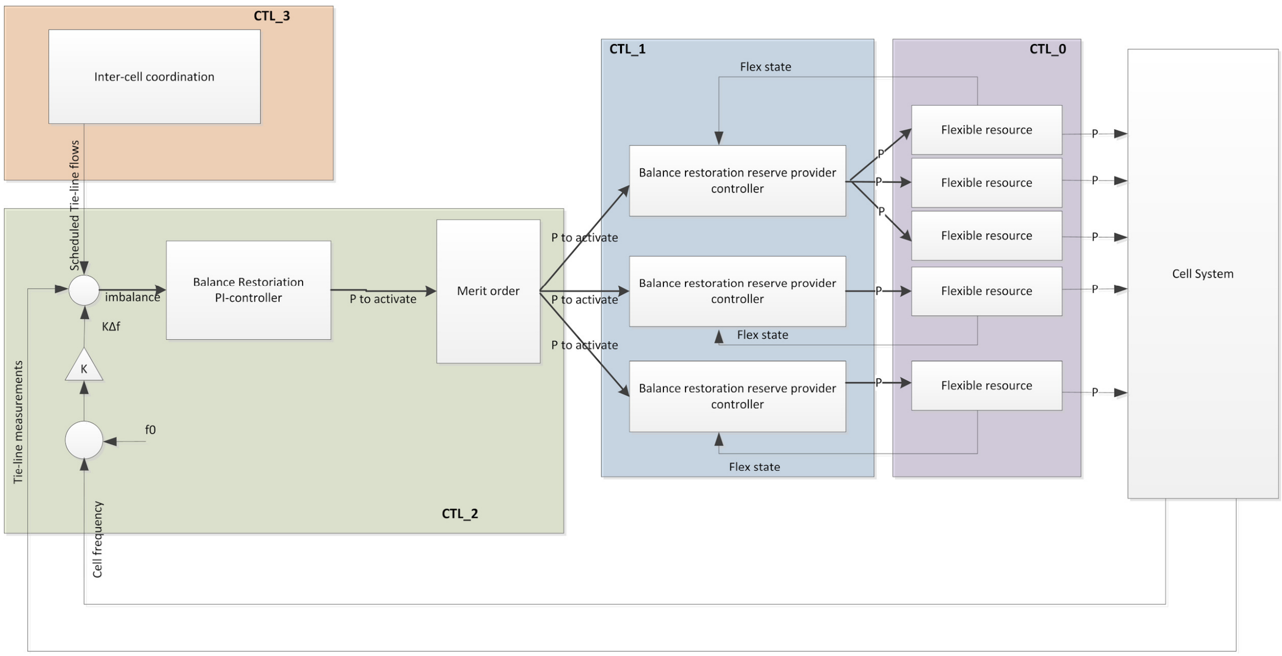

Figure 8: Balance Restoration Control: real-time control phase, variant 1.

4.2.2.1.1. CTL_3

The control objective of the controller is the calculation of the scheduled inter-cell tie-line flows. Based on these tie-line flow calculations, the imbalance signal will be calculated.
Observables for this CTL3 controller are all forecasted or predicted power production and demand within the cells.
The output signal of the CTL3 controller are the calculated scheduled tie-line flows.
Timing of the controller: The schedules can only be calculated after all market-procedures have been concluded, but should happen before t0.

4.2.2.1.2. CTL_2

The control objective of the controller at CTL_2 level is the provision of a reserve activation signal for each of the restoration reserve providers, based on the previously defined merit order and based on the measured imbalance in the cell. To avoid grid congestion issues, the (updated) cell system state information can be taken into account when defining the reserve activation signals.
The amount of reserves to activate is defined through a PI-controller, with the cell imbalance as input signal.
Observable or input for this CTL2 controller is the cell imbalance. The cell imbalance is defined as the difference between scheduled tie-line flows and measured tie-line flows, corrected with the FCC contribution of the cell resources (indicated in the Figure as K*Δf).
A second input is the cell system state information, this can be taken into account when determining which reserve should be activated, to avoid grid congestion issues.
The output of the CTL2 controller is a restoration activation signal for each restoration reserve provider: the activation signal should contain how much reserves should be activated for how long.

Timing of the controller: The reserve activation signals should be present in the order of minutes after an imbalance occurs.

4.2.2.1.3. CTL_1

The control objective of the controller at CTL_1 level is the activation of the required capacity taking account the state of the flexible resources within the portfolio. After a predefined ramp-up time, the required capacity should be activated by sending the necessary activation signals to certain resources within the providers' portfolio.
Observables or inputs for this CTL_1 controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.
The output of the CTL_1 controller is an activation signal to each (or a selection) of the resources within the portfolio.
Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance was detected. Therefore, the timing of the CTL_1 controller should be that the necessary activation signals are determined and sent within a timescale of a couple of minutes.

4.2.2.1.4. CTL_0

The control objective of the controller at CTL_0 level is the adequate response to a resource activation signal.
Observables or inputs for this CTL_0 controller are depending on the resource.
The output of the CTL_0 controller is a change of power exchange, dependent on the activation signal, with the cell system.
Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance was detected. Therefore, the timing of the CTL_0 controller should be that the necessary power change is realized at least before 15 minutes after the imbalance detection. Ramp-up times of different resources may differ.

4.2.2.2. Variant 2

Variant 2 of the BRC real time control phase is developed, because for some cell systems, such as for example LV-cells, a prediction of the grid state is very hard to obtain since too many parameters (such as renewable resource production, power consumption of small groups of consumers, etc.) have a very low predictability.
In that case, it is almost impossible to take a prediction of the cell system state into account when the merit order for reserves is determined. One possible option to prevent grid congestion issues during BRC, is to take grid prevention measures at the activation time of the resources.
The variant controller is mainly defined at CTL_0 level.

Real-time control phase

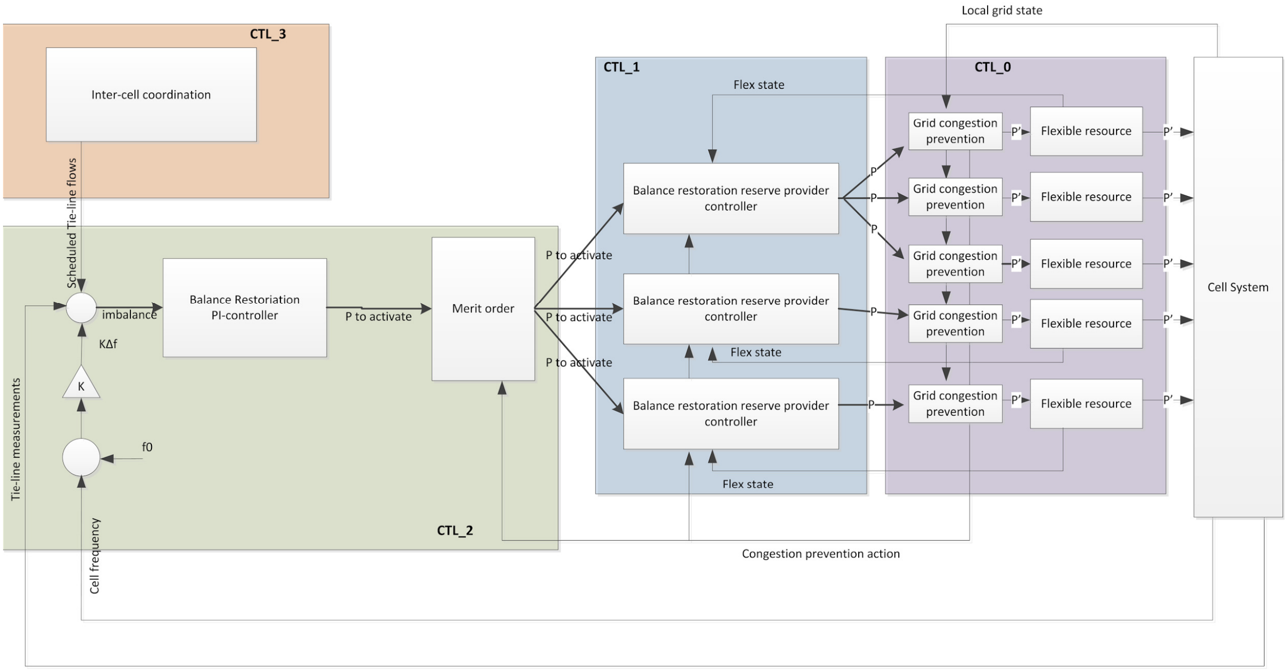

Figure 9: Balance Restoration Control: real-time control phase, variant 2.

4.2.2.2.1. CTL_3

The control objective of the controller is the calculation of the scheduled inter-cell tie-line flows. Based on these tie-line flow calculations, the imbalance signal will be calculated.
Observables for this CTL3 controller are all forecasted or predicted power production and demand within the cells.
The output signal of the CTL3 controller are the calculated scheduled tie-line flows.
Timing of the controller: The schedules can only be calculated after all market-procedures have been concluded, but should happen before t0.

4.2.2.2.2. CTL_2

The control objective of the controller at CTL_2 level is the provision of a reserve activation signal for each of the restoration reserve providers, based on the previously defined merit order and based on the measured imbalance in the cell. If a certain restoration reserve provider informs that because of grid congestion issues he cannot provide the necessary capacity, subsequent reserve providers are activated to eventually obtain the required restoration reserve.
The amount of reserves to activate is defined through a PI-controller, with the cell imbalance as input signal.
Observable or input for this CTL2 controller is the cell imbalance. The cell imbalance is defined as the difference between scheduled tie-line flows and measured tie-line flows, corrected with the FCC contribution of the cell resources (indicated in the Figure as K*Δf).
The output of the CTL2 controller is a restoration activation signal for each restoration reserve provider: the activation signal should contain how much reserves should be activated for how long.
Timing of the controller: The reserve activation signals should be present in the order of minutes after an imbalance occurs.

4.2.2.2.3. CTL_1

The control objective of the controller at CTL_1 level is the activation of the required capacity taking account the state of the flexible resources within the portfolio. After a predefined ramp-up time, the required capacity should be activated by sending the necessary activation signals to certain resources within the providers' portfolio. When because of grid congestion issue prevention, a certain resource is not activated (see CTL_0 controller below), the CTL_1 controller should redispatch the required activation capacity within his portfolio. If this is not possible, this should be noticed to the CTL_2 controller, so that other restoration reserve providers can be activated.

Observables or inputs for this CTL_1 controller are the flexibility state of the resources within the portfolio of the reserve restoration provider.

The output of the CTL_1 controller is an activation signal to each (or a selection) of the resources within the portfolio.

Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance was detected. Therefore, the timing of the CTL_1 controller should be that the necessary activation signals are determined and sent within a timescale of a couple of minutes.

4.2.2.2.4. CTL_0

The control objective of the controller at CTL_0 level is the adequate response to a resource activation signal. When activation according to the required signal would cause grid congestion issues, based on the local grid state, the resource activation signal is altered to prevent grid congestion issues by a grid congestion prevention control. For example, if the local grid voltage at the connection point of the resource is quite low, and the resource is required to consume more, the grid congestion prevention can alter the activation signal to prevent under voltage issues.

Observables or inputs for this CTL_0 controller are depending on the resource. An indication of the local grid state, e.g. a local voltage measurement, is required for the grid congestion prevention control.

The output of the CTL_0 controller is a change of power exchange, dependent on the activation signal, with the cell system. If grid congestion prevention has caused a difference in resource activation, this is reported to the CTL_1 and CTL_2 control so that subsequent measures can be taken.

Timing of the controller: activation of the reserve capacity should be at least before 15 minutes after an imbalance was detected. Therefore, the timing of the CTL_0 controller should be that the necessary power change is realized at least before 15 minutes after the imbalance detection. Ramp-up times of different resources may differ.

5. Technical description - Use Case Balance Steering Control (B4.BSC)

5.1. Background

Balance Steering Control (BSC) is responsible for providing the required amounts of flexible power in order to mitigate imbalances and support system stability. In a sense, the functionality of BSC is similar to conventional tertiary frequency control, which aims at substituting reserves activated during imbalance incidents by secondary frequency control. In the classical approach, this functionality is sufficient to provide the operators with the time and capacity reserves in order to cope with incidents. However, as the system is developing with the substantial shift to DER from centralised generation and unidirectional power flows, the system behaviour imposes the necessity for a different approach in terms of real-time balancing services. For instance, large amounts of RES can cause frequent fluctuations due to intermittent operation. These fluctuations are further complicated by the possibility of fluctuations in consumption due to increased flexibility. By contrast, in the current system's view of operation there are no such concerns for the operators which can cope with imbalance incidents by considering the worst case scenarios like the loss of a large generating unit. All these factors that shape the identity of future grids advocate the view that operators should take special measures against such kinds of frequent imbalances that may threaten system stability. This can be facilitated by flexibility of resources, and by diversity that may lead to cost-effective operation and implementation of applications that provide operators and balance control schemes with accurate data forecasts that can be used to mitigate imbalances - not only after incidents but also proactively. In this context, the ELECTRA view of Balance Steering Control is described in the following sections.

5.2. Objectives in ELECTRA context

Due to the above-described requirements of future grids, the ELECTRA Balance Steering Control is responsible for:

- Substitution of implemented reserves after imbalance incidents (reactively)
- Mitigation of imminent imbalances (proactively)

It is obvious that the first objective of BSC is similar to the classical tertiary control, namely the substitution of reserves used by Balance Restoration Control. This action is done by using resources of flexibility mainly within the cell in which imbalance has happened but, if necessary, the operator can invoke resources from adjoining cells, thus modifying on purpose the agreed interchanges only for the duration of BSC activation. Since this mode comes as the reaction of BSC to an imbalance incident it is regarded as reactive, thus distinguishing it from the mode described below.

In addition, an extra functionality for BSC has been considered in ELECTRA involving proactive operation. This means that if an accurate short term forecast is available regarding imbalances, resources can be used so as to reduce the imminent imbalance. This leads to either completely eliminating the need for other control actions or substantially reducing the reserve needs for IRPC, FCC, and BRC.

In both of the abovementioned modes of BSC, there is always an overarching objective that concerns the control implementation. That is the cost-effective implementation of resources which is obtained in real-time by specific control algorithms aiming at minimising a cost function. Since the major factor concerning the cost-effective operation of resources is Operation and Maintenance Cost, which depends on the operating point of each unit, it can be assumed that the scope of this control will be the maximisation of efficiency. In this case efficiency is used instead of the absolute cost as a normalised cost function.

5.3. Control process

The sequence of actions, which are necessary for the effective BSC operation, are listed below:

Procurement phase:

- Flexibility providers (resource owners) submit availability to BRPs. The latter assess and aggregates flexibility for use in Ancillary Services market process.
- The market operator determines production/consumption schedules and informs all relevant actors including cell operators and reserve allocators.
- Reserve allocators, using data from the market operator, cell operators, and BRPs, plan requirements and schedules for BSC resources.
- Finally, BRPs assign resource owners with the specific flexibility to be made available upon request.
- Note: The definitions of BRPs, market operator, and reserve allocators are those given by ENTSO-E in the Harmonised Electricity Market-Role Model document.

Proactive mode:

- Initially, and under normal operation, the control block of BSC is informed of the reserve capacity of BSC resources.
- At a second step, the forecasting block initiates the calculation process for estimating imminent imbalances. The output of the forecasting block is nothing more that the setpoint of the aggregated power that the BSC control block will have to fulfil.

Reactive mode:

- As soon as BRC has been activated from a previous incident, the forecasting block is (temporarily) substituted by another control block that determines the set-point of the active power that BSC should fulfil. The calculation of the set-point is based on the reserves already activated by BRC.

As soon as the setpoint is determined by either approach, the next steps are common for both proactive and reactive Mode:

- BSC controller dispatches resources.
- The state and the aggregated power of these resources are continuously observed for comparison with the set-point value.
- Also, this observation is used for efficiency calculation.
- Finally BSC controller updates dispatching so as to minimise the error of power deviation and at the same time maximise efficiency of the selected portfolio.

The last part of the process lasts from 15 min to 1 hour according to the system needs.

5.4. Control Layers for BSC

The hierarchical structure of BSC involves two main layers, namely CTL-2 and CTL-3. In principle, BSC consists of a cascaded control and therefore the active resources located at CTL-1 and CTL-0 are essentially not depicted in the overall process. In fact, the set-point values derived by dispatching are sent to the resources' local controllers which can then modify their output power in order to meet the request. The main control layers alongside their objectives are shown in the following table.

Table 10: Control topology levels and control functions for Balance Steering Control

Control Topology Level	Control function
CTL-3	Determine available capacity of BSC resources via procurement phase
CTL-2	• Proactively mitigate imminent imbalances • Reactively substitute BRC reserves already active from previous actions • Minimise Operation and Maintenance Cost of deployed resources
CTL-1	Fulfil an active power set-point (this is a general function not specific to BSC only)
CTL-0	Fulfil an active power set-point (this is a general function not specific to BSC only)

CTL-3: Represents the domain of Web-of-Cells in which market processes take place between actors (roles) which or who determine not only the general operating requirements but most importantly determine availability of BSC resources. It is noteworthy that despite being intended to be used in a cell domain, due to the fact that BSC control can invoke resources from adjoining cells, the procurement mechanism must overarch cell domains. Therefore, this process is related to CTL-3.

CTL-2: Represents the domain of cells. All basic functionalities, such as forecasting, observation, efficiency calculation, and optimal dispatching are performed at CTL-2. Obviously the controller makes use of input data from CTL-3 and produces output to lower levels, thereby shaping a cascaded control configuration.

CTL-1 and CTL-0 involve Resource and Single Device domains. Their scope is to receive a set-point for power and fulfil it by means of a local control loop, which can be generic and used for other applications too and not only for BSC purposes. In this respect these levels have been omitted from the BSC descriptions.

5.5. Composition of Control Triples for BSC control functions

The composition of control triples for BSC follows the methodology described in Section 2.1.7.2.

5.5.1. Step 1

Main Use Case: B4.BSC (Balance Control; Balance Steering Control)

Control Objective 1 (proactive mode): "Respond to imminent imbalance forecasts by deploying resources to alleviate imbalance effects"

Control Objective 2 (reactive mode): “Substitute BRC reserves and maintain balance for the next time frames”

Control Objective 3 (both in proactive and reactive modes): “Observe and maximise efficiency of used resources portfolio”

5.5.2. Step 2

In the table below an overview of the control triples needed for BSC implementation is provided.

Table 11: Control Triples for Balance Steering Control

Control Topology Level	Control Time Scale	Control Aim	WP5 Observable	WP5 System Input Signal
2.Cell level	CTS_3 3.Tertiary Level	Substitute aggregated reserves [W]	Active power of aggregated resources [W]	Deployment of Active Power of aggregated resources [W]
3.Inter-cell level	CTS_3 3.Tertiary Level	Achieve a minimum of Reserve Capacity [W]	Availability of Flexible Resources [W]	Aggregated active power capacity [W]
2.Cell level	CTS_3 3.Tertiary Level	Mitigate imminent Imbalances [W]	Active power of aggregated resources [W]	Deployment of Active Power of aggregated resources [W]
2.Cell level	CTS_3 3.Tertiary Level	Maximise Operation & Maintenance efficiency of aggregated resources [1]	Operation & Maintenance efficiency of aggregated resources [1]	Deployment of Active Power of aggregated resources [W]

5.5.3. Step 3

Both control schemes at CTL-3 and CTL-2 are described as cascaded controllers since they derive signals to be used by lower level controllers. Eventually, these processes end up at CTL-1 and CTL-0 where general purpose power controllers are used to control the output power of individual resources/devices. The black-box diagrams below describe only the processes of CTL-3 and CTL-2 respectively.

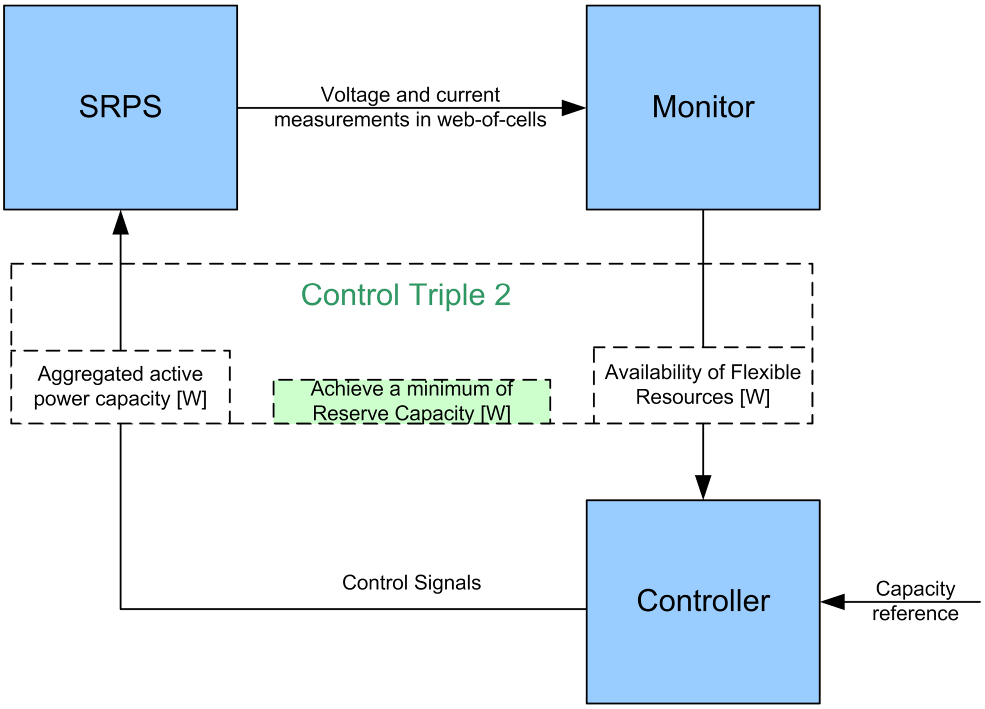

Figure 10: Control Loop diagram for Cascaded BSC. This diagram refers to CTL-3 with the objective of ensuring a minimum reserve capacity via procurement

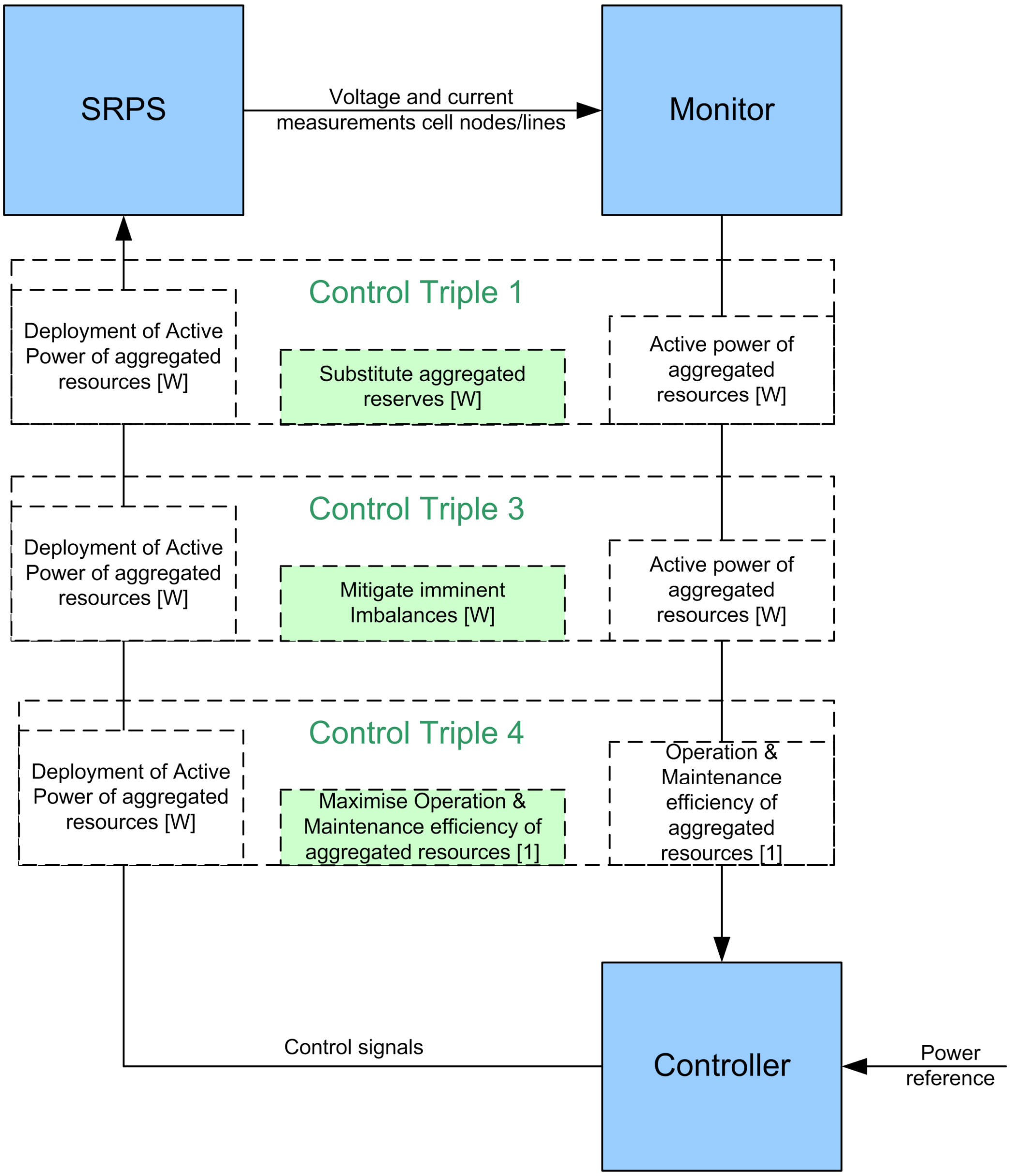

Figure 11: Control Loop diagram for Cascaded BSC. This diagram refers to CTL-2 with the objectives of fulfilling a power set-point with contemporary cost minimisation

6. Technical description - Use Case Primary Voltage Control (T1.PVC)

6.1. Background

Primary voltage control is meant to provide fast response to changing operating conditions, either with respect to measured quantities (mainly voltage) or reference values, but also control system parameters (such as droop coefficient, etc.). The speed of response expressed in terms of time units depends on the type of the flexible resource acting in the process ranging from close-to-instantaneous reaction of power electronic interfaced units, through slower response of conventional synchronous generators, to very slow acting devices possibly encompassing hysteresis, dead-band or delay functions in control algorithm (e.g. transformers). Irrespective of the time needed for the resource to act, PVC is intended to constitute the only means of controlling the voltage in an instantaneous manner, which effectively resembles primary control of voltage in today's power system. There are two differences, however, which bring in needs for new algorithms and decision making processes:

- PVC is intended to operate at all voltage levels, which means that different level of R/X ratio peculiar to different voltage levels in the grid will play an important role in defining whether a given resource should act via its reactive or active power output (or both) in order to control voltage in the most (cost) effective manner – this is an important advancement from what is used today;
- Resulting from the above, is the inclusion of any resource type that is available in the network to contribute to PVC – in principle every possible resource can be considered a flexibility resource, and this includes loads, storage, and RES which currently do not normally contribute to voltage control.

6.2. Objectives in ELECTRA context

The main aim of PVC is to maintain the required value of voltage at a measurement point which can coincide with the point of interconnection of the controlled resource or another point in the network. The reference value for PVC is received from post-primary voltage control or directly from the cell operator. The control signal fed to the unit is achieved by means of a proper regulator action (e.g. PI, PI with droop, or more complex AVR-like schemes, etc.). This signal in most cases is equivalent to the unit's required reactive power, but it can also be active power (where active power is used for controlling voltage) or other control signal for devices equipped with internal voltage regulators (i.e. more complex flexibility resources like HVDC links, some FACTS devices, or other).

Another objective of PVC is to enable selection of either active or reactive power as a control signal for voltage regulation. This is accomplished by introducing droop characteristics into control schemes (refer to ELECTRA D3.1, Section 5.1.1 "Narrative of Use Case") by defining droop coefficients for active and reactive power, n_p and n_q, respectively.

6.3. Control layers for Primary Voltage Control (PVC)

Table 12: Control Topology Levels for Primary Voltage Control

Control Topology Level	Control function
CTL-3	Not applicable for voltage control.
CTL-2	Cell operator sets the voltage setpoints to voltage control service provider such as generating units, synchronous condensers, capacitors.
CTL-1	The service provider, such as an aggregator, activates the flexible resources.
CTL-0	The local device responds to the voltage set-points by adjusting the active and/or reactive power.

6.4. Composition of Control Triples for PVC control functions

The steps in Chapter "2.1.7.2. Composition of Control Aims/triples for control functions" are followed.

6.4.1. Step 1

Main Use Case: T1.PVC (Voltage Control; Primary Voltage Control)

Deliverable D3.1 Control Objective: "Minimise transient voltage deviations."

6.4.2. Step 2

The following control triples are chosen as building blocks.

Table 13: Control Triples for Primary Voltage control

Topology layer	UC.CTL	Control Time Scale	WP5 Control Aim	WP5 Observable	WP5 System Input Signal
CTL_1 Flexible resource level	T1.PVC.CTL_1	CTS_1 1.Primary Level	17-Minimise transient voltage deviations [V]	Actual node voltage [V]	Complex power of aggregated resources [VA]
CTL_0 Physical device level	T1.PVC.CTL_0	CTS_1 1.Primary Level	10-Minimise transient voltage deviations [V]	Actual node voltage [V]	Reactive power of synchronous generator/compensator [VAr]

6.4.3. Step 3

Both control triples include flexible resources. CTL_1, however, assumes utilising aggregated resources such as a virtual power plant. CTL_0 uses single devices having capability of voltage control, among which there are synchronous generators, loads, storage, and FACTS devices. CTL_0 in the figure 12 has been depicted only for a synchronous generator example.

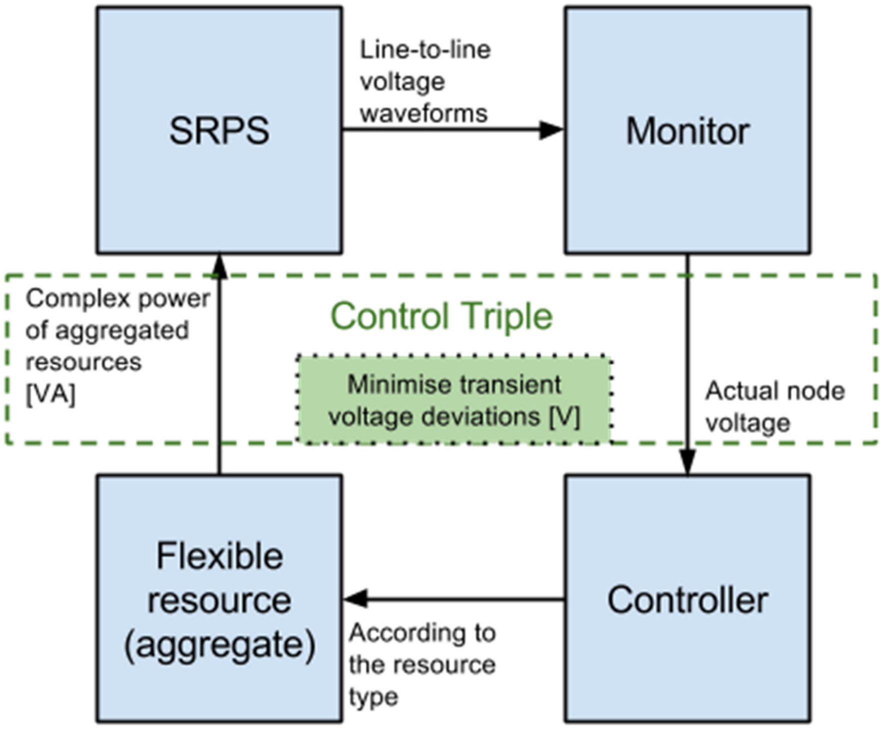

Figure 12: Control Loop diagram for PVC. This diagram refers to CTL_1.

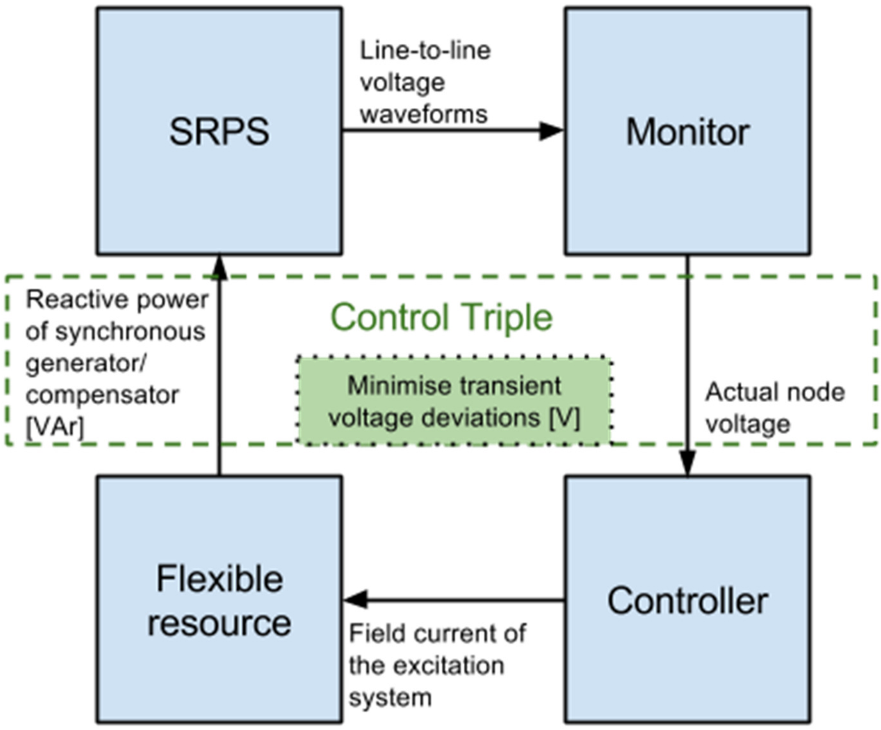

Figure 13: Control Loop diagram for PVC. This diagram refers to CTL_0.

7. Technical description - Use Case Post Primary Voltage Control (T2.PPVC)

7.1. Background

The novel control scheme proposed by ELECTRA 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.

The control aim for primary control is the stabilization of the voltage level in case of a severe disturbance by adjusting the reactive power (or active power in networks with high R/X ratio, like LV grids) injection at the point of interconnection of the device or at a very close node. Primary voltage control is an automatic control accomplished by fast-acting devices such as the automatic voltage controllers (AVRs) of the generation groups. It operates in the range of milliseconds. Based on this, by regulating the reactive (and in some cases the active) power flows, the voltage in the node sits close to the required set-point.

On the other hand, once the voltage has been stabilised by the PVC after a voltage problem, the PPVC restores voltage levels in the nodes of the cells to their rated values (within a safe band) while optimizing the distribution of the reactive power flows in the cell (reduction of the losses of the network). The PPVC mechanism substitutes conventional secondary and tertiary voltage control schemes. It acts at cell level in the range of secondary control times (few seconds up to one minute).

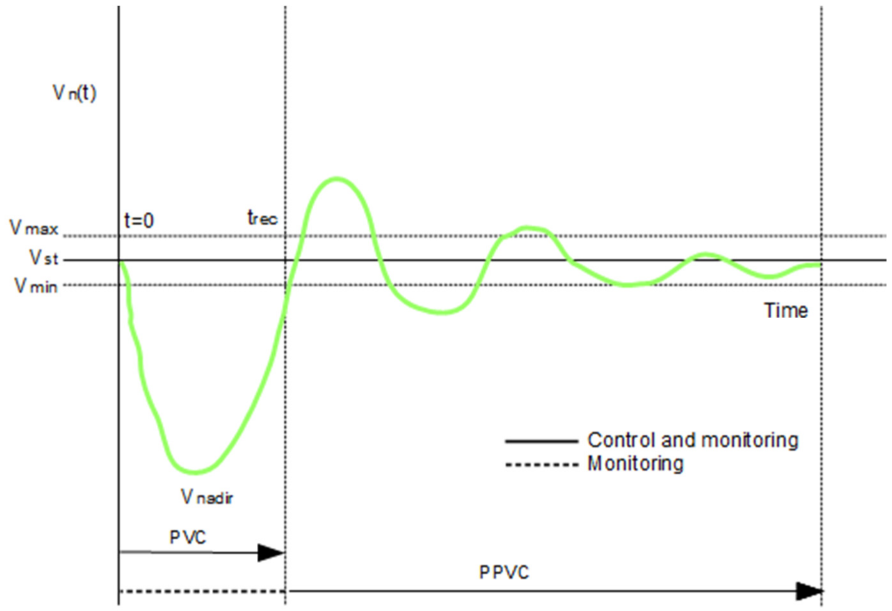

Figure 14: Evolution of RMS voltage profile and voltage control domain

To avoid the activation of the PVC and the problems that a voltage incident can provoke in a cell, the PPVC is also continuously acting in a proactive way to activate resources in advance, based on short-term forecasts of the cell state.

7.2. Objectives in ELECTRA context

Following the voltage control architecture as defined in ELECTRA [ref. D3.1], post-primary voltage control can be activated in two ways:

a) After the primary voltage control execution.

In this case, the control objective of the PPVC is to restore voltage levels to pre-incident values while optimizing reactive power flows (minimizing the losses).

b) Proactive PPVC in normal cell operation.

In this case, the control objective of the PPVC is to mitigate over/undervoltages by the activation of reserves in advance while optimizing reactive power flows.

7.3. Control process

The PPVC control process follows the sequence:

- (Prerequisite) Reserves are contracted by agreement between PPVC resource providers (and cell operators of neighbouring cells with extra-capacity) and the cell operator of the cell under analysis.
- Monitoring system provides real-time measurements of voltage and current waveforms.
- Corresponding observables are calculated from the real-time measurements in nodes: vector of voltage phasors (RMS amplitude, phase), and vector of complex powers (P, Q) in cell nodes and lines.
- To compensate the associated error of the measurements and a potential unavailability of some measurements, a State Estimation process is launched providing the real state of the cell.
- The real cell state is the input for the calculation of the voltage error/deviation. If a voltage value in one of the nodes is out of the tolerance band, the system sends an error signal to activate the process for PPVC provision.
- Short-term forecast of observables: in the proactive mode of operation of the PPVC mechanism the present observables (calculated from real-time measurements) are used jointly with additional information (short-term meteorological prediction, etc.) to provide a short-term forecast of these observables (so-called “predicted observables”), which will be the input of the state estimation (“predicted state of the cell”). The rest of the process is identical from this point: voltage deviation calculation, availability checking of resources, etc. (see below).
- The Cell Operator checks the availability of its self-procured PPVC reserves that had previously participated in the PPVC market.
- The cell operator runs an optimal power flow (OPF) analysis, verifies that no congestion problems are produced and dispatches the different resources optimally.
- The cell operator restores the required voltage set-point by sending the activation order to the different reserves through the PPVC resource providers (set-points for PVC resource controllers and controllers of PPVC resources not participating in PVC).

The complete description of this Use Case and the corresponding control sequence can be found in section 11.6 (Annex B).

7.4. Control layers for PPVC

The PPVC is achieved by means of a layered control structure.

Table 14: Control topology layers and control functions for Post Primary Control

Control Topology Level	Control function
CTL-3	Not applicable for voltage control
CTL-2	Keeping (restoring) node voltage levels within the established band while optimizing reactive power flows (minimizing the losses) at cell level
CTL-1	Set-point allocation to flexibility resources to provide the PPVC service
CTL-0	--

CTL-2: After a voltage problem in a cell that requires the starting up of the PVC, the voltage deviation is stabilized when the fast PVC resources are activated in the cell. Then the PPVC mechanism takes over with the commitment to bring the voltage levels in the nodes of the cell back to the established values while optimizing the reactive power flows in order to reduce the losses in the network. When the voltage deviation is detected in a cell node based on measurements, observables, and the calculation of the state of the cell (State Estimator), the cell operator checks the availability of its own cell resources and those in the neighbouring cells previously agreed/contracted, runs an OPF analysis to obtain the optimal dispatching, and sends the corresponding set-points to the PPVC resource providers and neighbouring cell operators (CTL-1).

CTL-2: In normal conditions of the cell (no voltage incident and therefore no activation of PVC mechanism), the PPVC is still continuously (periodically) running trying to anticipate voltage problems. Based on short-term forecast of the node voltages, the PPVC is proactively mitigating voltage deviations by the activation in advance of the appropriate reserves also optimizing the reactive power flows. This is a cost-effective solution since it avoids the activation of the PVC mechanism, always guaranteeing that the voltage levels are within the established band.

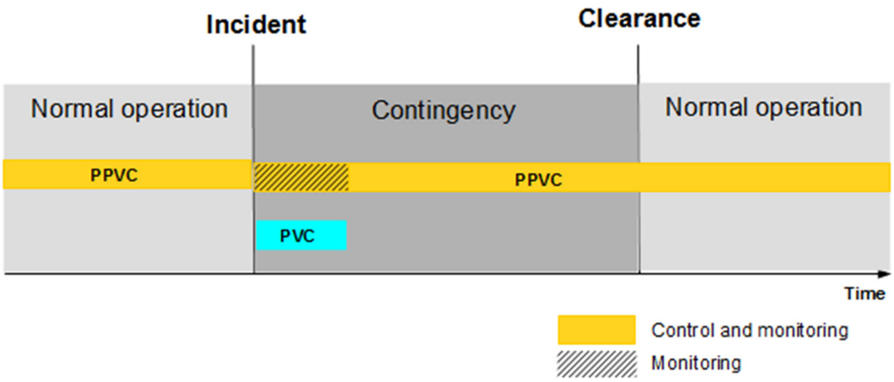

Figure 15: Activation timeframes for voltage control schemes

From the control scheme viewpoint, the "proactive PPVC" process is identical to the "PPVC after PVC" activation, except for: (1) use of "predicted observables" instead of "present observables", (2) "proactive PPVC" is periodically running (depending on the availability of the needed information for the short-term forecast, for example, the short-term meteorological prediction), while the "PPVC after PVC" only runs after the execution of the PVC in case of a severe voltage problem.

7.5. Composition of Control Triples for PPVC control functions

Following the methodological steps of Chapter "2.1.7.2. Composition of Control Aims/triples for control functions" for the PPVC mechanism:

7.5.1. Step 1

Main Use Case: T2.PPVC (Voltage Control; Post-Primary Voltage Control)

Control objective 1 (in case of a voltage incident): "Restore voltage levels to pre-incident values while optimizing reactive power flows"

Control objective 2 (in normal operation): "Proactively mitigate over/undervoltages while optimizing reactive power flows"

7.5.2. Step 2

The filtered list of control triples for PPVC can be found in this online spreadsheet:
Accepted Subcases-PPVC

The control triples to be used as building blocks can be found in the following table.

Table 15: Control Triples for Post Primary Control

<table>
<tr><th>Topology layer</th><th>UC.CTL</th><th>Control Time Scale</th><th>WP5 Control Aim</th><th>WP5 Observable</th><th>WP5 System Input Signal</th></tr>
<tr><td rowspan="8">CTL_2
Cell level</td><td rowspan="8">T2.PPVC.CTL_2</td><td rowspan="4">CTS_2
2. Secondary Level</td><td rowspan="4">Restore voltage levels to pre-incident values while optimizing reactive power flows</td><td rowspan="2">Vector of voltage phasors [V,rad]</td><td>Optimal voltage set-points to DERs [V]</td></tr>
<tr><td>Active power set-points to DERs [W]</td></tr>
<tr><td rowspan="2">Vector of complex power [VA]</td><td>Optimal voltage set-points to DERs [V]</td></tr>
<tr><td>Active power set-points to DERs [W]</td></tr>
<tr><td rowspan="4">CTS_3
3. Tertiary Level</td><td rowspan="4">Proactive over/undervoltages mitigation</td><td>Vector of voltage phasors [V,rad]</td><td>Optimal voltage set-points to DERs [V]</td></tr>
<tr><td>Vector of voltage phasors [V,rad]</td><td>Active power set-points to DERs [W]</td></tr>
<tr><td>Vector of complex power [VA]</td><td>Optimal voltage set-points to DERs [V]</td></tr>
<tr><td>Vector of complex power [VA]</td><td>Active power set-points to DERs [W]</td></tr>
</table>

7.5.3. Step 3 and Step 4

The PPVC control objectives will be achieved by means of a cascaded control solution. PPVC corresponds to the top layer where no flexible resources are present. The output of the PPVC mechanism (cell global optimisation) is a cluster of set-points for the different flexible resources, i.e. the bottom layer corresponds to the PVC control loop (different control loops depending on the specific technology of the employed flexible resource).

In addition, in this case up to four different but interrelated and simultaneous control triples are needed for achieving each control aim. When the PPVC is activated after the PVC execution (a voltage incident has occurred), the controller is using directly the observables calculated from the real-time measurements. The diagram is the following one:

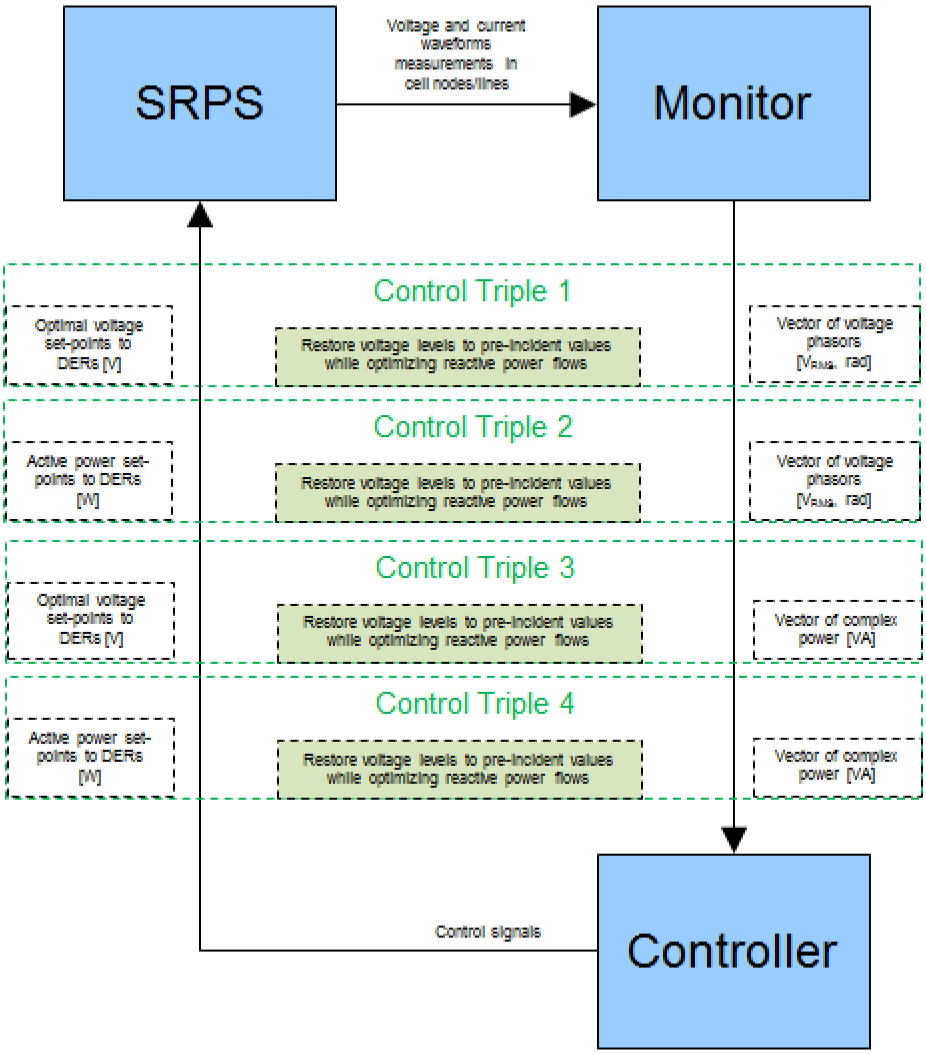

Figure 16: Control Loop diagram for PPVC after PVC (top layer)

Analogously, when the PPVC is running in normal operation (no voltage incident and therefore no PVC activation), the measurements and observables (input to the controller) are identical, but in this case, the first stage inside the controller black box is a short-term forecast. The output of the controller (control signals) is again identical (even when in this case are based on forecast rather than real-time measurements). The diagram is the following one:

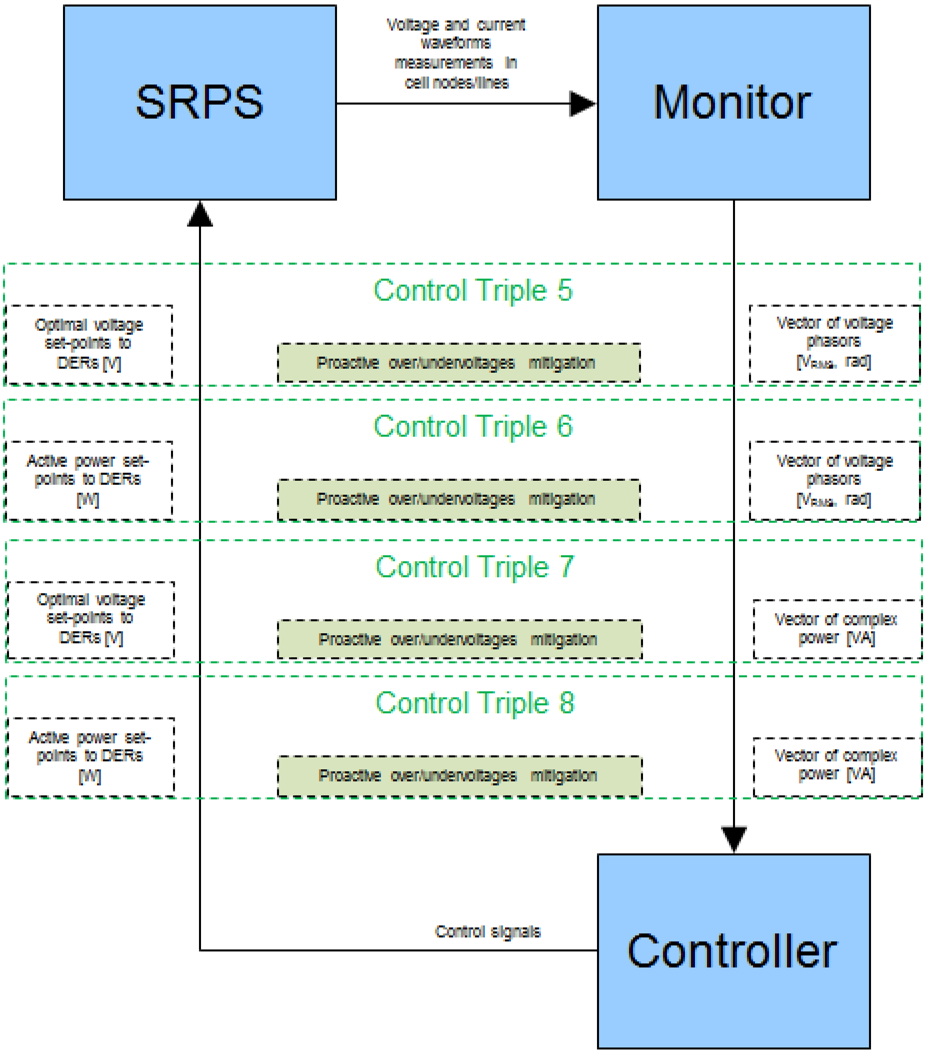

Figure 17: Control Loop diagram for Proactive PPVC (top layer)

In both cases, the bottom layer corresponds to PVC control loops (see previous section 10.5). For illustrative purposes, one of these loops is presented below for inverter-based DERs:

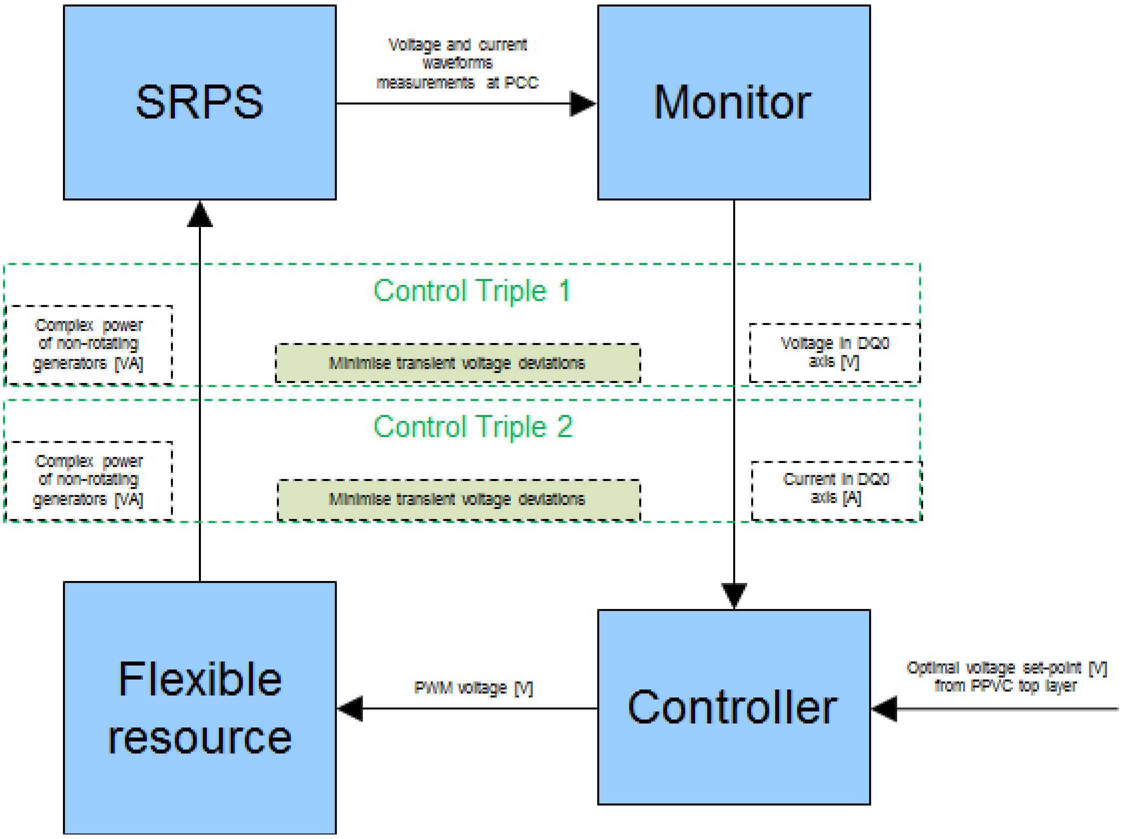

Figure 18: Control Loop diagram for PVC (bottom layer) receiving a set-point from PPVC Control Loop (top layer)