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ELECTRA

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

WP 5

The Web-of-Cells control architecture for operating the future power systems

Deliverable 5.3

A distributed control scheme for Balancing and Voltage Control in the Power System 2030+

ELECTRA Web-of-Cells Task Force

09/04/2018

ID&Title	D5.3 The ELECTRA Web-of-Cells Architecture in a Nutshell	Number of pages:	44

Short description (Max. 50 words):

The document briefly describes the Web-of-Cells (WoC) architecture for balance and voltage control in the power system 2030+, developed within the Integrated Research Programme ELECTRA. The WoC assumes a novel organization of the power system into cells, where power balancing and other functionalities are performed within specific areas, following the paradigm of solving local problems locally.

The concept proposes a decentralized control scheme, focusing on local inter-cell tie-line power flow deviations. The Web-of-Cells concept key assumptions, the associated control functions, the different roles and the interaction with the market processes are described in this deliverable in addition to the very detailed deliverables on these individual aspects.

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Executive summary

The ELECTRA Integrated Research Programme (IRP) on smart grids brings together the partners of the EERA Joint Programme on Smart Grids (JP SG) to reinforce and accelerate Europe's medium to long term research cooperation in this area and to drive a closer integration of the research programmes of the participating organizations and of the related national programmes. ELECTRA's joint research activity and collaborative support actions build on an established track record of collaboration and engagement. The project consortium of leading research organisations from 17 different European countries aims to reinforce the EERA JP SG in strengthening coordinated European research, and building support for realizing the European SET Plan objectives in the area of smart grids.

It is assumed that in the future power system, generation will shift from classical dispatchable units to intermittent renewables and CHP. As a consequence, a great part of the generation will shift from few large units to many smaller units. Electrical energy storage is expected to be a cost-effective solution for offering ancillary services that stabilise the system and fill the momentarily gap between system generation and system load. Next to this, it is presumed that the power system observability will increase due to more ubiquitous sensors and a large amount of fast reacting distributed resources will be able to offer reserves capacity.

In light of this trends, the RTD related aim of ELECTRA is to research innovative control solutions for real-time voltage and balancing (frequency) control in the 2030+ power system, utilizing flexibility from across traditional boundaries in a holistic fashion and building on ubiquitous sensing and dynamic/autonomous control functions.

The document describes the Web-of-Cells (WoC) architecture for balance and voltage control in the power system 2030+, developed within the Integrated Research Programme ELECTRA. The WoC assumes a novel organisation of the power system into cells, where power balancing and other functionalities are performed within specific areas, following the paradigm of solving local problems locally. The concept proposes a distributed control scheme, focusing on local inter-cell tie-line power flow deviations.

The Web-of-Cells concept key assumptions, the associated control functions, the different roles and the interaction with the market processes are described in this deliverable, as well the required steps to transfer the WoC approach into the power system.

Terminologies

Abbreviations

AS	Ancillary Services
BP	Bidding Process
BRC	Balance Restoration Control
BRP	Balancing Responsible Party
BSC	Balance Steering Control
BSP	Balance and Voltage Control Service Providers
CC	Cell Controller
CCGT	Combined Cycle Gas Turbine
CoBA	Coordinated Balancing Area
CP	Clearing Process
CPFC	Cell Power Frequency Characteristics
CSO	Cell System Operator
CTL	Control Topology Level
DA	Day Ahead
DNO	Distribution Network Operator
DSO	Distribution System Operator
ELECTRA	European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids
ESCO	Energy Service Company
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FCC	Frequency Containment Control
FRC	Frequency Restoration Control
GHG	Greenhouse Gas
HV	High Voltage
IEAM	Internal Electricity Market
ICT	Information and Communication Technology
ICZGCT	Intraday Cross-Zonal Gate Closure Time
ID	Intra Day
IoT	Internet of Things
IRP	Integrated Research Program
IRPC	Inertia Response Power Control
HV	High Voltage
LV	Low Voltage
MCP	Market Clearing Price
MOC	Merit Order Collection
MOD	Merit Order Decision
MV	Medium Voltage
NPFC	Network Power Frequency Characteristics
OLTC	On-load-tap-changer-transformer
OPF	Optimal Power Flow
PMU	Phasor Measurement Unit
PP	Power Plant
PPVC	Post Primary Voltage Control
PVC	Primary Voltage Control
RA	Regulatory Authority
RES	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
SS	System Services
TRL	Technology Readiness Level
TSO	Transmission System Operator

VPP	Virtual Power Plant
WoC	Web-of-Cells

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1 Introduction

1.1 Purpose and scope of the report

This document describes a distributed control scheme for balance and voltage control for the future (2030+) power system developed within the Integrated Research Program (IRP) ELECTRA. Based on a number of widely accepted trends regarding the 2030+ power system, a new control architecture for reserves activation that better addresses the fundamental changes of the future power system is proposed. The focus is on a control architecture related to the **real-time reserves activation** by the system operators, both to correct for real-time imbalances – and thus frequency deviations – caused by residual imbalances left over by the balancing responsible parties (BRPs) as a result of forecast errors or incidents, as well as to regulate voltages. To emphasize: the scope of the ELECTRA IRP is the control that takes place **after** the market parties ended their market-balancing activities (t_0) and it addresses real-time deviations compared to the scheduled balance resulting from forecast errors (in load or generation) or incidents (Figure 1), in order to ensure voltage and frequency (balancing) control in the future power system.

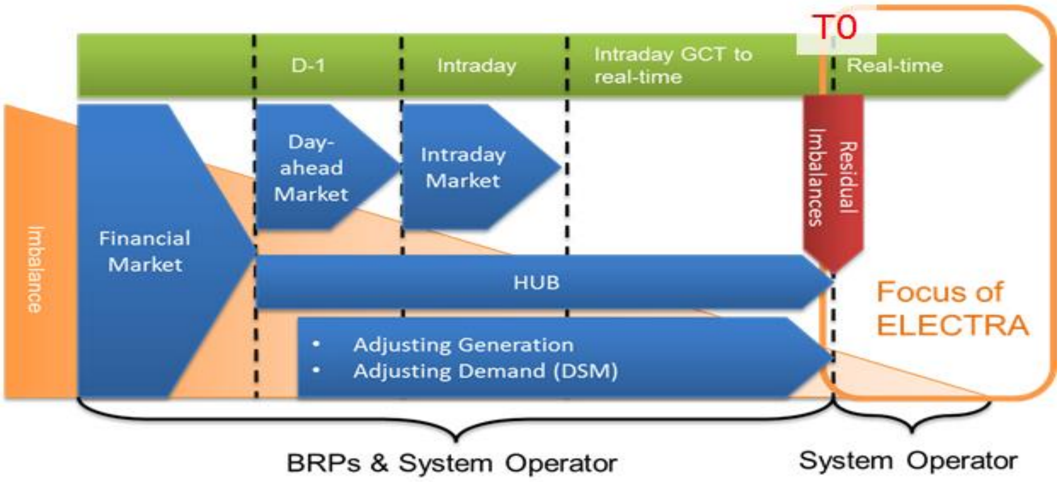


Figure 1: ELECTRA focus and Timeline of Balancing Procedure

It is expected that due to the forthcoming changes, the future frequency and voltage control can no longer be effectively managed in a transmission system operator (TSO) central manner. Instead, a radically new approach is required, that leverages innovative monitoring systems based on a fully instrumented network, and dynamic autonomous distributed control functions. In order to regain reliable control over the power grid, also distributed generators and loads should and will be controlled in a way manage the continuous stream of imbalances as perceived system-wide by the TSO's.

Maintaining the present centralised detection and activation paradigm requires a lot of detailed local information to be collected, aggregated and communicated from all low voltage (LV) and medium voltage (MV) networks to the high voltage (HV) TSO to allow it to detect local problems, and to determine a secure and optimal reserves activation action using distributed (flexible) resources. For these reasons, ELECTRA IRP proposes a distributed control scheme, called Web-of-Cells (WoC) concept described in this document. The IRP ELECTRA is targeting the time horizon 2030+, thus a proof of concept of the WoC is performed mainly using simulations and lab-scale validation.

1.2 Limitations of the study

The developments and validations, supported by simulation and lab experiments in ELECTRA IRP, so far support the viability of WoC as a concept. However, there are several limitations, within the scope of ELECTRA IRP.

Uncertainties related to configuration of the future power system: The initial idea is that Web-of-Cells will perform better than conventional controls in a future power system, which will be radically different from the existing approach. There are still some uncertainties related to the configuration of the future system, which are impossible to tackle in detail in ELECTRA IRP. Even if the solutions designed within the project will be most probably valid according to the expected trends in power systems evolution by 2030+, it is still difficult to benchmark the WoC concept against the conventional system of controls due to these uncertainties.

Limited project period and available test base: WoC as a concept has been proposed and elaborated during a fairly short project period with a limited test base available in the project. It appears that several aspects are difficult to be verified - especially on lab-level - during the project. For example a comprehensively evaluation of scalability and replicability issues of a scaled-up system with numerous cells.

Market aspects: In addition to the physical dimension, one should also consider the market-related limitations. The concept presumes that several challenges will be resolved by introduction of specific market solutions and tries to elaborate an proposal for these. Market modelling is however a very demanding task and is not the primary focus of the present project, because the market solutions must be defined after the technical solutions are validated.

Technology Readiness Level: As planned, the technology readiness level (TRL) of ELECTRA IRP outcomes reaches 3 to 4, being TRL4 “Prototype or component validation under laboratory conditions”. TRL5 and beyond are for pre-commercialization and testing of prototypes under real or field conditions, and are clearly beyond the ELECTRA scope. So, the developments around the Web-of-Cells concept within ELECTRA are focusing on lab-scale level. Since ELECTRA IRP mainly focuses on the proof of concept of the WoC approach further investigations of the above listed limitations should be elaborated in subsequent research activities.

Comparing the proposed cell-based control concept with similar innovative ideas (microgrids, fractal grids, etc.) it is necessary to mention that some of the questions or details may not be possible to clarify in principle. This for example applies to a dimension or size of a cell in the WoC context; as well as in microgrids or even Load Frequency Control Areas (LFCAs), the size can be various, depending upon several conditions. In summary, this means the WoC definition in ELECTRA IRP provides a proven concept as well as corresponding guidelines and rules in order to structure and control the future power system.

2 The ELECTRA key assumptions that impact future voltage and frequency control

The Web-of-Cells concept has been proven as flexible enough to cope with the operational problems that are projected to arise in many scenarios. In other words, ELECTRA proposes control solutions not related to a specific scenario, but instead related to **a number of clear and indisputable trends that fit multiple future scenarios** [see ELECTRA D3.1]. The main aspects of these trends are the following:

- **Generation will shift from classical dispatchable units to intermittent renewables**
  The European Commission's Reference Scenario 2016 [1] foresees that electricity coming from Renewable Energy Sources (RES) will increase, as a share of net power generation, from around 20% in 2010 to 42% in 2030 (see Figure 1). Variable RES (solar and wind) are expected to reach around 19% of total net electricity generation in 2020, 25% in 2030 and 36% in 2050. This will result in:
  - Paradigm shift from generation following load to load following generation.
  - Increased need for balancing reserves activations.

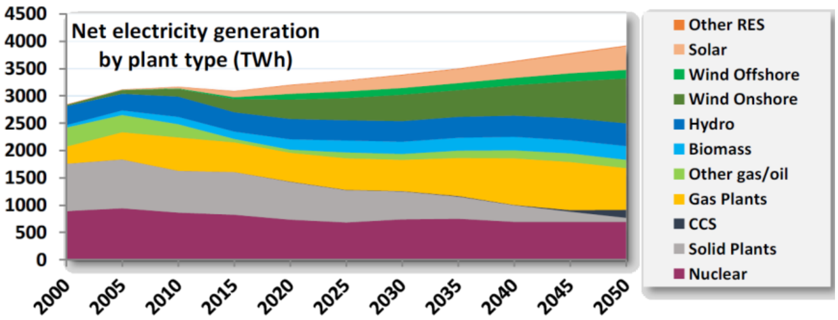


Figure 2: Electricity generation per plant type [1]

- **Generation will shift from relatively few large units to many smaller units**
  Electricity generation is shifting from a few large central power plants to many smaller units connected mainly at the distribution level. In addition to the smaller units, there will still remain large central power generators, being increasingly more of a RES nature (e.g. large wind-power plants (onshore and offshore), hydro-electric power plants, and marine energy parks).
  - There will be more locations – and chances – where deviations compared to what was forecasted and planned, and incidents (like generation outages) can happen, but each individual incident will have a smaller – local – impact.
  - Local – i.e. distribution system level - incidents may have a local impact that goes unnoticed at a system global level
  - There will be a shift from synchronous generators to power electronics interfaced generation reducing the power system inertia and causing a higher Rate Of Change Of Frequency (ROCOF), more spurious tripping of protection relays, and short activation times for frequency containment reserves.
  - Since the power system production portfolio is subjected to changes throughout the day (renewable generators are weather and time dependent), power system time constants and response times will constantly change.

- **Generation will substantially shift from central transmission system connected generation to decentralized distribution system connected generation**
  - More injection at LV and MV distribution grid increases the risk of local voltage problems and congestions (especially given the expected increase in electricity consumption)
  - Resources that can help to address voltage and balancing problems will move to a large extent, from central transmission system level (HV) to distribution system level (MV/LV). Also the resources, that can help to address voltage and balancing problems, i.e. resources that can provide ancillary reserves support will move, in a high percentage, from central transmission system level (HV) to distribution system level (MV/LV).
  - A central system operator at transmission level no longer has the system overview to effectively dispatch reserves so coordination between operators of different voltage levels will be essential.
  - The distribution and availability of resources (production as well as storage) may vary significantly from geographical location to location.

- **Electricity consumption will increase significantly**
  Due to the greenhouse gas (GHG) emission reduction targets, there is a drive towards the electrification of transport and heating/cooling, resulting in an expected increase of the electricity consumption. As a result, grids will be used closer to their limits. Besides, a large fraction of the increased load will be actively controlled and/or responding to market signals, making – local – consumption forecasting even more challenging.

- **Electrical storage will be a cost-effective solution for offering ancillary services**
  According to the recommendations for a European Energy Storage Technology Development Roadmap [7], prices of (electrical) storage are projected to drop, making distributed storage a competitive solution compared to traditional resources for reserve services. Furthermore, the energy storage roadmap claims that distributed storage located at a utility substation on the distribution grid has a much higher value than central storage because it offers distribution upgrade deferral and circuit stability control. Such storage devices are well suited to deal with continuous, small up and down fluctuations caused by intermittency and forecasting errors. Moreover, they have a larger flexibility range in both power flow directions and usually a fast reaction time.

- **Ubiquitous sensors will vastly increase the power system's observability**
  With the proliferation of distributed generation, and the price of sensors and solutions set to fall dramatically over the next few years, the inclusion of sensing and monitoring systems is starting to make compelling economic sense. It is essential for providing grid operators with a holistic view of the grid and its critical components [3]. This will result in many more measurement points at all voltage levels, such as phasor measurement units (PMU's) and smart metering infrastructure.

- **Large amounts of fast reacting distributed resources (can) offer reserves capacity**
  Vast amounts of controllable loads, local storage and converter-coupled energy sources will be available at all voltage levels (especially at the low voltage levels), providing very fast reaction and ramp times. These distributed resources can offer their flexibility capability as a service (e.g. balance restoration, frequency containment, congestion management) to grid operators and market parties [4].

  - There will be a large number of distributed resources with a large variety (production as well as consumption and storage resources), that will be able to provide Frequency Containment Reserves (possibly imposed participation through regulation) and/or Balance Restoration Reserves.

- In future, local reserves will not be more expensive than central ones. A lot of related functionalities, such as voltage and frequency support, are already mandatory now (e.g. PV inverters). Even in presence of a market for related services a lot of flexibility will be available resulting in low prices.
- In future, local reserves activations might be (almost) cost free (e.g. shifting consumption)

- **Developments in Information and Communication Technologies will support the pathway towards more decentralized or distributed managed power systems**
  The developments of information and communication technologies (ICT) and their massive introduction in the power system in the last decades completely changed the methods for monitoring, operating and planning. Without the possibility of data generation as well as related data and information exchange even liberalisation of the energy sector would not have been possible. Currently also the last mile of the power system is about to be covered by ICT, supporting also the massive integration of small-scale generation, prosumers, storage, e-mobility and demand response. This will be additionally supported considering the progress and developments concerning internet of things (IoT) as well as big data. IoT can lead to a completely rethinking of LV grid operation use cases. The amount of IoT-ready appliance (sensors, meters, inverters, home management systems, etc.) in low voltage grids is surging. These appliances can be used for additional services like forecasts of load, generation and flexibility requests.

3 Motivation for a new control architecture

Based on the ELECTRA assumptions as outlined in the previous section, the present grid management structure and organization for frequency and voltage control, with the TSO being responsible for reserves activation in its Control Area, will not be effective at addressing these emerging challenges [5-6].

Today's approach, with the TSO as central actor responsible for the management of ancillary services for voltage and frequency control has proven effective because (and as long as) power flows are mainly unidirectional downstream, and the resources for reserves needed to address frequency (or balance) issues and voltage problems, are (mainly) located centrally at the HV level. Their activation only affects this unidirectional downstream power flow. However, with the shift toward distributed systems, a new control architecture may be more appropriate. Two future architectures are considered:

1. A (still) **centrally managed future**, where frequency and voltage control is managed by the TSO which controls reserves located both at distribution grid level and at transmission grid level. The TSO remains responsible for the real-time reserves activation and dispatching within its Control Area / Control Block.

Challenges for a centrally managed future:

- Local problems, related to the larger share of RES generation located at the distribution grid level, will or may not be noticed and handled by the TSO at system level due to information overload. For example, voltage issues on the local distribution grid due to increased production of RES may remain unnoticed by the TSO if many other operating issues occur concurrently.
- In order to identify problems and to detect the need for reserves activations as well as to ensure secure and efficient activations of distribution grid connected reserves providing resources, many sensors, communication and data aggregation are required, leading to higher complexity and delays (bottom-up and top-down). The TSO just cannot check everything in sufficient detail (due to the complexity and computation time, as well as communication time).
- With the increasing amount of intermittent RES generation at distribution grid level, there will be an increasing amount of residual local imbalances that may counterbalance each other at system level. Local imbalances caused by forecasting errors may result in insecure local load flows, i.e. 'additional' power flows compared to the scheduled setpoint flows may cause congestions or overloading of tie lines without triggering central – restoration - frequency control. However, even in case this would not lead to congestions, it would lead to losses in case reserves would be activated in an (geographical) area that is at a large distance from where the imbalance (i.e. deviation from the scheduled balance) is located.
- As already identified in Section 2, the drive towards higher efficiencies and lower emissions will lead to further electrification in the fields of heating, cooling and transport. This will create the need for power system that can offer these additional services by utilizing existing flexibility in the system with no or minimal additional network reinforcements. This demand flexibility will be further enhanced by smart inverter technologies that will create rewarding synergies in managing distributed generation with distributed storage. These identified benefits can only be managed through active distributed control with minimal but important interfacing with central systems for

integrated control.

- The European policy for Nearly Zero Energy Buildings will transform the energy use towards being local with self-consumption to the highest level possible. These targeted solutions will push self-consumption of local generation to optimal levels that have a strong local characteristic. Optimal solutions will be sought and this will utilise distributed storage (of available electric vehicles complemented with privately owned storage facilities) that can optimally be aggregated through effective distributed control.
- DGs, distributed storage and demand side flexibility generate a wealth of data required for primary control for system to operate optimally in a global way. This generated data in order to be effective requires fast and error-free interpretation that will lead to operational actions of the primary equipment at local level. For this to be effective it requires that all decisions that call for local actions should be taken locally and pass centrally only the necessary aggregated data that will be useful for the global control and operation of the system.

2. A **decentralized managed future**, with a high share of flexibility providing resources at distribution system level and the possibility of local sensing, monitoring and control. This enables to divide the power system in smaller grid areas, called Cells, which can provide local balancing and voltage control with the purpose of solving local problems locally.
    - Each cell has assigned an operator – Cell System Operator (CSO) who takes responsibility for the real-time reserves activation and dispatching in its own cell(s) (i.e. assuming responsibility similar to former TSO responsibility in its Control Area).
    - In each cell, the operator maintains an accurate view on the cell state, and dispatches reserves located in the cell in a secure manner based on its knowledge of the cell state. In principle, no global system state information is required for this. In this way, a ‘divide and conquer’ way of tackling voltage and balancing issues is implemented. For this the Cell System Operator may rely on other actors/roles (like Flexibility Service providers).
    - In this way, local problems are resolved locally, in the cell (simple and effective control paradigm) in a fast and secure manner, limiting complexity and communication overhead (i.e. no bidirectional communication between the DSO(s) and conventional centralised TSO is required for reserve activation). There is no need to expose local problems at global system level.
    - Next to the benefits related to solving local problems locally (reducing losses, mitigating congestion risks, limiting communication data volume, cost and time), this as well allows for a more optimal use of the available grid capacity thanks to a divide-and-conquer benefit. This is enabled because due to the smaller dimensions and complexity of a cell, load flow checks and optimizations for instance can be done to an extent that would be computationally not feasible for centralised TSO control.

4 The Web-of-Cells architecture

4.1 Cell-based architecture for decentralized balancing and voltage control

The foreseen massive availability of flexible energy resources, mainly connected to the grid at distribution system level, leads to the idea that a decentralized or distributed control concept, aimed to solve local problems locally, will best address the fundamental changes in the future power system. For that reason, ELECTRA proposes a new cell-based distributed control framework named Web-of-Cells (WoC). In this view the power system is split into control cells.

An ELECTRA Cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate the cell generation and load uncertainties in normal operation.

In line with the above definition:

- an ELECTRA Cell is connected to one or more neighbouring cells via one or more physical tie-lines;
- there is no restriction in how cells are interconnected;
- an ELECTRA Cell can span one or more voltage levels;
- it is not required that a cell is self-sufficient (capable to balance internal generation and load), but this case is possible;

Considering the ownership and the responsibility of a tie-line(s) between cells, these are always assigned to one of the linked cells. In this way the physical boundaries of a cell may also include some tie-lines.

Each cell is managed by a so-called Cell Controller (CC). The CC is under the responsibility of a Cell System Operator (CSO) role that supervise its operation and, if needed, is able to override it. A Cell System Operator (present DSO/TSO) can operate multiple cells, each one having its own CC, that can also be non-adjacent.
The CC includes functions and services conventionally provided by DNOs, DSOs, and TSOs or by new network operators. Roles and responsibilities are detailed in section 4.5, and the functions required for the CC are summarized in section 4.2.

It is anticipated that the CC will provide autonomous control of balance/frequency and voltage. This could radically change the present centralized power system control paradigm, involving a central TSO control room/centre, towards an highly automated real-time control with reduced human operator involvement.

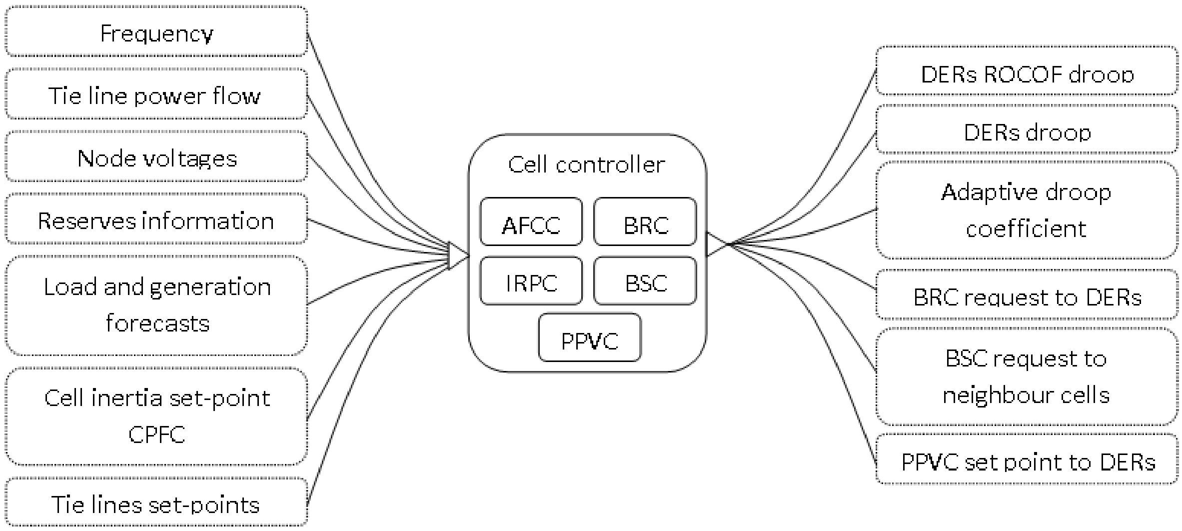


Figure 3: Cell controller input and output

In figure 4, an example of WoC is presented, which demonstrates different types of cells in terms of internal topology and cell interconnections.

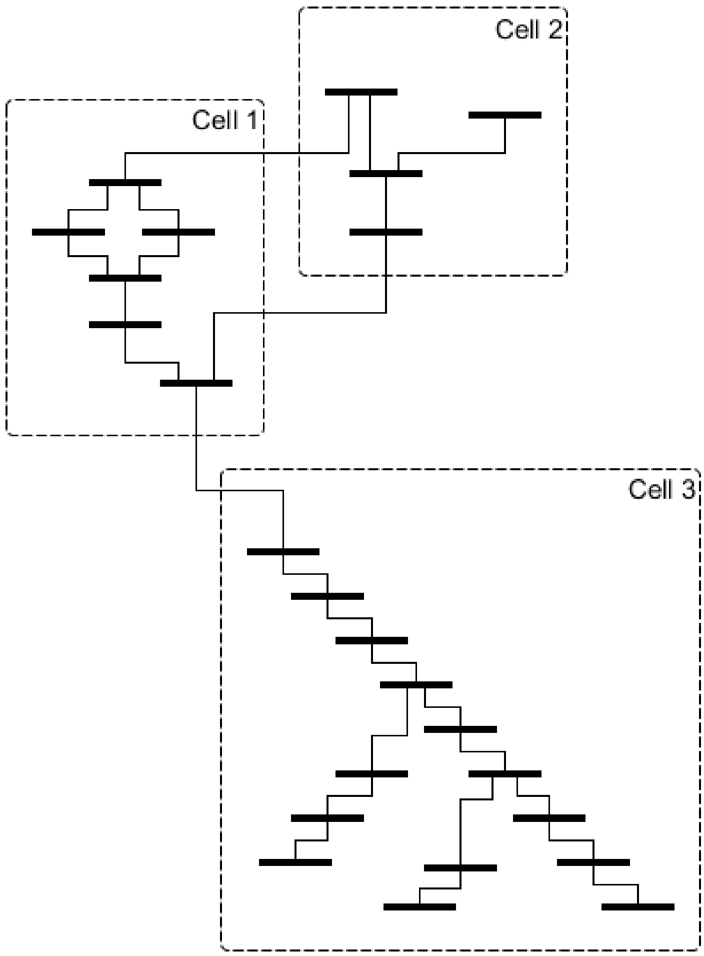


Figure 4: Web of Cell example

The cell definition includes as a special case a cell that has only one connection point with the rest of the system and with enough resources to be self-sufficient. This type of cells may be able to operate both in grid-connected and in island mode and in this case they can be considered as microgrids. Therefore, a microgrid could be seen as a special type of cell.

4.2 Web-of-Cells operation modes and related functions

In order to maintain frequency (balancing) and voltage control in the future power system, the WoC control scheme introduces six high-level use cases, which are Balance Restoration Control (BRC), adaptive Frequency Containment Control (aFCC), Inertia Response Power Control (IRPC), Balance Steering Control (BSC), Primary Voltage Control (PVC) and Post Primary Voltage Control (PPVC). These use cases are characterized by three fundamental characteristics:

- Solving local problems at cell level
- Responsibilization with local neighbor-to-neighbour collaboration
- Ensuring that only local reserves providing resources, where activation does not cause local grid problems, will be used

Cells are treated as 'physical clusters' with characteristics of a Virtual Power Plant (VPP) responsible for matching their actual net active power import/export profile to the forecasted profile (which relates to system balance). This is the responsibility of the **Balance Restoration Control (BRC)** functionality. The system balance (as well as frequency) is restored according to a bottom-up approach based on local observables (cell tie-line power flows). The cell setpoints correspond to a system balance and if each cell adheres to its setpoint, the system balance is kept. The proposed BRC shows resemblance to the present Frequency Restoration Control (FRC) responsible for restoring the system balance, in a centralised manner. In contrast to FRC, which is a secondary control and takes over from Frequency Containment Control (FCC), in the ELECTRA WoC concept the BRC runs at the same timescale as FCC and therefore contributes to frequency containment as well as balance/frequency restoration. Deviations observed by a cell can be caused by the cell itself, but also by neighbouring cells, so there is a level of local collaborative balance (and frequency) restoration.

For **Frequency Containment Control (FCC)** an adaptive functionality is proposed. It ensures that each cell adapts the amount of provided dP/df droop in response to real-time frequency and tie-line deviations from their nominal values. The output of this process is used as a multiplication coefficient for the nominal Cell Power Frequency Characteristic. The latter parameter is specified by a setpoint received from a system-level process. A cell central Frequency Droop Parameter Determination function receives the cell's CPFC setpoint (cell's contribution to the system NPFC – Network Power Frequency Characteristics) for the next timestep). The Merit Order Decision function ranks the available frequency droop devices based on cost and location. This is done based on availability and cost information received from these frequency droop devices, load and generation forecasts of all busses (nodes), and a local grid model. Location information is important to ensure that the power activations of the Frequency Droop devices will not cause local grid problems. The resulting ordered list is sent to the Frequency Droop Parameter Determination function determining the requested dP/df droop setting (which can also be 0) for each frequency droop device.

Each Frequency droop device receives its droop setting (droop slope and deadband) for the next timestep, and will continuously monitor df and activate/absorb active power in accordance to its droop setting. This setting is continuously modified by the adaptive CPFC determination function by means of a scaling factor determined based on the cell's imbalance state. Based on frequency and cell imbalance error signals, this function will calculate the scaling factor to ensure that most FCC activations are done in cells actually causing the deviation. This should mitigate the effect of causing cell imbalances (with subsequent BRC activations) in cells that otherwise would be in balance because of a blind reaction on a global observable (frequency deviation). This is the adaptive aspect. The idea behind this new approach is to make the frequency containment reserve activation as close as possible to the power disturbances. This adaptive FCC runs at the same timescale as the Balance Restoration Control and both join forces in containing frequency deviations.

As mentioned above, more and more grid integrated electricity generation is going to be converter based. All photovoltaic power plant as well as a high share of wind power plants already use converters as grid interfaces. Hence, the contribution of synchronous generators providing inertia through their rotating mass is expected to decline. Based on the actual energy mix the available inertia can vary wildly. For that reason, ELECTRA IRP has introduced an **Inertia Response Power Control (IRPC)** functionality, which ensures additional, synthetic inertia is supplied (by managing suitable flexible resources), to complement the physical inertia left in the system. A cell central df/dt droop slope determination function receives a cell's J (moment of inertia) setpoint (cell's contribution to the system inertia) for the next timestep. A merit order decision function ranks the available required rate of change of frequency (ROCOF) droop devices based on cost and location. This is done based on availability and cost information received from these ROCOF droop devices, load and generation forecasts of all buses (nodes), and a local grid model. As already remarked for FCC, location information is important to ensure that power activations of the ROCOF droop devices will not cause local grid problems. The resulting list is sent to the df/dt droop slope determination function that defines the requested df/dt droop slope setting (which can also be 0) for each ROCOF droop device. Each ROCOF droop device receives its droop setting for the next timestep, and will continuously monitor df/dt and activate/absorb power in accordance to its droop setting. No deadband will be used so that an action is taken even on the slightest variation of Δf/Δt. This choice is made to reap the side-effect of limiting the frequency fluctuation also during normal operation; i.e. the frequency fluctuation due to small variations of load and generation. A deadband combined with a low amount of inertia provided by synchronous generators could result in high frequency fluctuation tripping some of the connected generation.

To complete the Balance/Frequency Control related functionalities a **Balance Steering Control (BSC)** is introduced. The BSC tries to counteract the excessive amount of bottom-up BRC reserves activations in one cell, based on local observables and losing the possible benefits of imbalance netting from neighbouring cells. BSC implements a distributed/decentralized coordination scheme where neighbouring cells mutually agree on changing their tie-line active power flow setpoints – without violating operating limits - and this way reduce the amount of BRC reserves that would be activated in each cell. This can be considered as an implementation of an imbalance netting mechanism localized in the cell surrounds. Specifically, this use case will implement a corrective BSC functionality, which determines new setpoints for the BRC controller, thereby causing the deactivation of resources previously activated by BRC.

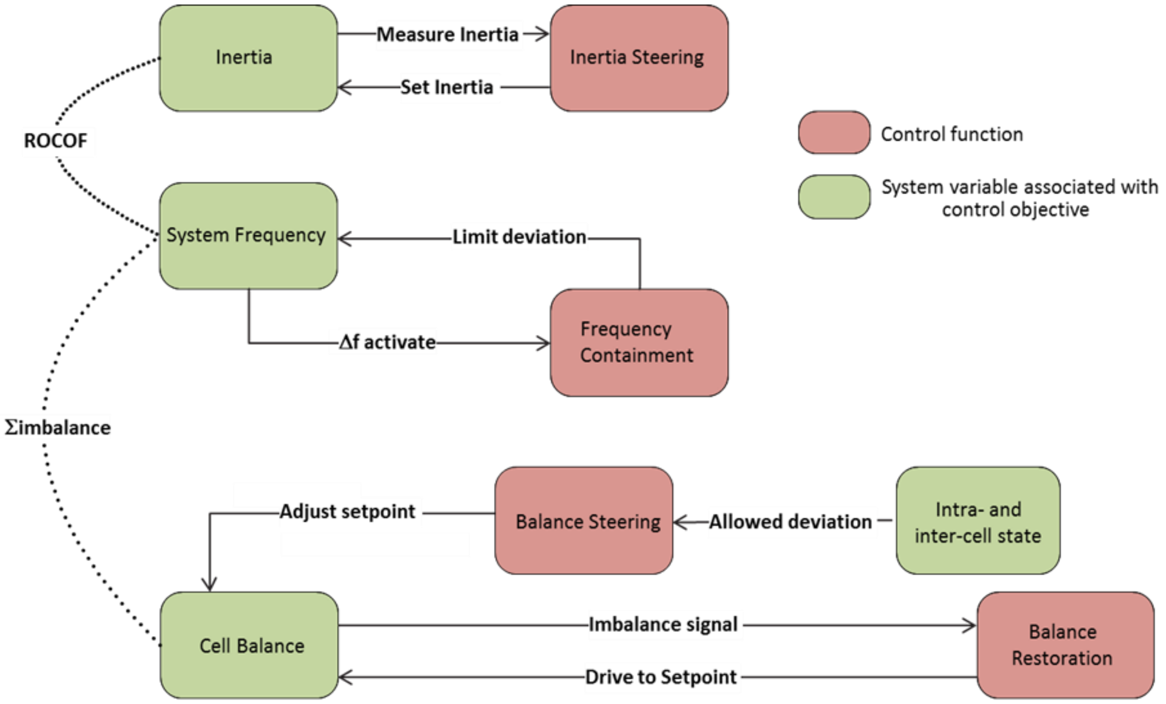


Figure 5: WoC balance control functions

The objective of cell voltage control functions (see Figure 6) is active at all voltage levels in a very dynamic manner: not only to correct voltage deviations that cause voltage limit violations, but to minimize power-flow losses too. The **Primary Voltage Control (PVC)** functionality, as it is already in use today, will be present at all voltage levels, and at LV and MV level it could influence a cell's balance.

Additionally, ELECTRA proposes a **Post-Primary Voltage Control (PPVC)** functionality determining setpoints for all resources able to contribute to voltage control (and loss minimization): like PVC (automated voltage regulation)-resources, Q-controllable resources, tap-changing transformers, capacitor banks. The cell central PPVC function is activated either by means of a system level trigger (proactive setpoint recalculation), or when one of the pilot nodes reports a voltage violation (i.e. a voltage deviation outside the limits: corrective setpoint recalculation). ELECTRA assumes there is no constant polling by the PPVC function of all pilot nodes, but that pilot nodes autonomously monitor their local voltage and send a signal when they detect a violation. On receipt of the activation trigger (timer or voltage violation error), the PPVC function will send a trigger signal to the PPVC setpoint providing function to initiate the calculation of new setpoints. As input for this setpoint calculation, information is collected from the (voltage) reserves information provider function (availability of voltage reserves), the tie-line powerflow setpoint provider function (reactive power-flow profile setpoint at the cell tielines), and the load & generation forecast providing function (load and generation forecasts). For implementing this functionality, a local grid model is assumed to be available. Based on all this information, the PPVC setpoint providing function performs an Optimal Power Flow (OPF) to calculate voltage setpoint settings keeping all nodes within the limits according to valid standards and minimizing powerflow losses in the cell. The PPVC controlling function then sends the calculated setpoints to the PVC droop nodes, controllable Q nodes, capacitor banks and On-load-tap-changer-transformers (OLTCs).

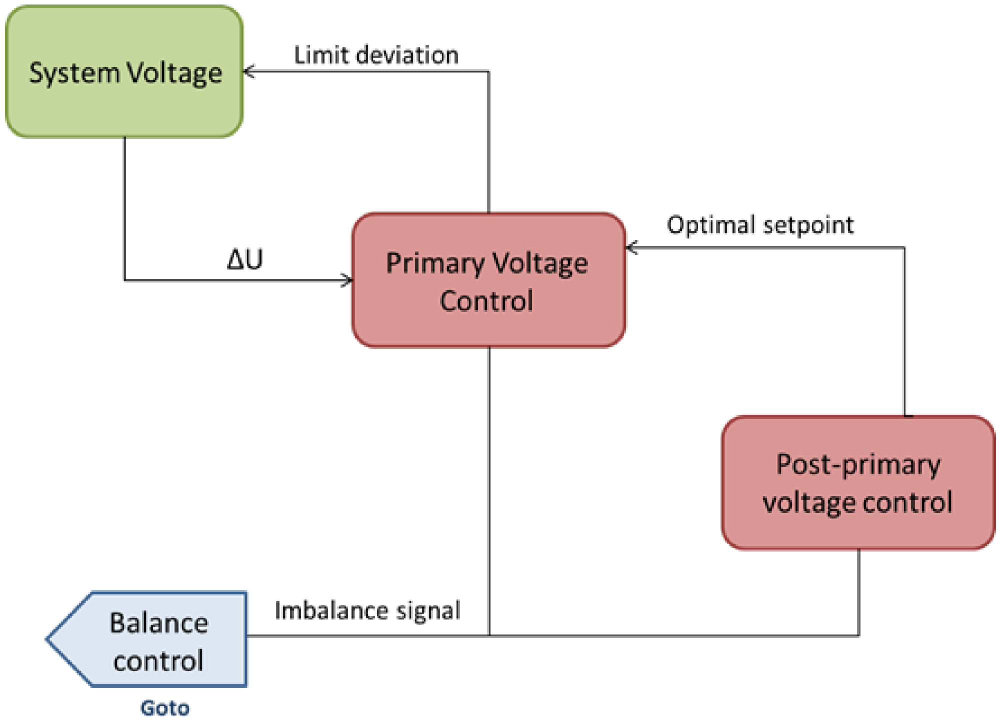


Figure 6: WoC voltage control functions

In course of the development and validation activities two different kind of functions have been distinguished:

- **In focus functions** of the specific use case / functionality: mainly at CTL-2/3 level. Functions(/Device) related to **observables** (input for detecting if a corrective action is needed) or **actuations** (e.g. activating power to realize the correction): mainly at CTL-0/1 level.
- **Supportive functions** that are needed for testing and validation, but are not part of the control loop itself and can be emulated (e.g. using a database or file read access of previously stored values). Examples are functions that provide load and generation forecasts.

As already presented above some of these functions are used for several use cases. The following table gives an overview of all use cases and the related control, observe and actor functions. More details on the related control functions are presented in the ELECTRA Deliverables 6.3, whereas simulation results are reported in D6.4.

ELECTRA Use Case	Related WoC control (c), observer (o) and actuator (a) functions – in scope	Related WoC control functions – supportive
Balance Restoration Control (BRC)	• Merit Order Collection (c) • Merit Order Decision (c) • Imbalance Determination(c) • Imbalance Correction (c) • Tie-line Active Power Observation (o) • Tie-Line Active Power Setpoint Provider (a)	• Reserves Information Provider • Load & Generator Forecaster • DER – Controllable P device
Adaptive Frequency Containment Control (aFCC)	• Frequency Droop Parameter Determination (c) • Merit Order Collection (c) • Merit Order Decision (c) • Adaptive CPFC Determination (c) • Frequency Observation (o) • (BRC) Imbalance Determination (c)	• Cell CPFC Setpoint Provider • Reserves Information Provider • Load & Generator Forecaster • DER – ROCOF droop device
Inertia Response Power Control (IRPC)	• Merit Order Collection (c) • Merit Order Decision (c) • df/dt Droop Slope Determination (c) • (BRC) Imbalance Determination (c)	• Cell Inertia Setpoint Provider • Reserves Information provider • Load and Generator Forecaster • DER – ROCOF droop device
Balance Steering Control (BSC)	• Tie-line Limits Calculation (c) • Cell Setpoint Adjusting (c) • Tie-line Active Power Observation (o) • Imbalance Determination (BRC) (c)	• Tie-Line Active Powerflow Setpoint provider
Primary Voltage Control (PVC)	• DER – AVR device (a)	
Post Primary Voltage Control (PPVC)	• PPVC Controlling (c) • PPVC Set-point Providing (c) • Voltage Pilot Nodes (o) • DER – AVR Device (a) • DER – Controllable Q Device (a) • Capacitor banks (a) • OLTC (a)	• Reserves Information Provider • Load & Generator Forecaster • Tie-Line Powerflow Setpoint Provider

Figure 7: ELECTRA Web-of-Cells use cases and the related control, observe and actor functions

4.3 Cell cooperation and interconnection operating modes

For the further analysis and evaluation of cell cooperation and interconnection operating modes a selection has been made addressing mainly the combination of balancing and frequency control (i.e., IRPC and FCC; FCC and BRC; FCC, BRC and BSC), as well as voltage control (i.e., PVC and PPVC) use cases taking the laboratory capabilities of the ELECTRA partners and the stakeholders feedback (i.e., CIRED Workshop 2016) into account.

The analytical and experimental assessments in the work undertaken have demonstrated the suitability of the proposed control approaches for the dynamically changing power system of the future. The experimental evaluation was an important step towards proving the ability of the proposed controls to perform under almost real-world conditions implemented in the laboratories. While the simulations already highlighted the benefits of these controls over state-of-the-art, it remained unclear whether these fundamentally new approaches would perform satisfactorily outside idealised simulated conditions. Therefore, the conducted experiments where imperative to highlight the real-world applicability of the proposed controls. The resilience of the proposed controllers to communications asynchronicity, finite measurement and control step resolution, various noise sources, parameter uncertainties, and other factors not explicitly incorporated in the mathematical model were tested in the process as well. The deployment of the controllers on dedicated controller hardware enabled rapid prototyping, allowing for an efficient iterative development process by feeding back experiences made under real conditions into the theoretical method.

The following observations have been made:

- *Balancing and frequency control with focus on FCC and BRC use case combination*
  With the development of the balancing control functions (FCC and BRC) and their validation in a laboratory environment, the promise of the WoC concept has been delivered, i.e., the ability of more decentralized and distributed operation of power system has been proven. Furthermore, the developed controls, in essence work towards the objective of solving local problems locally. Beginning with the speculation of advantages of more local control, this exercise has proven some merits of prioritizing of local response to a local imbalance, such as improved dynamic response, robust reserve activations and reducing the divergence from planned system conditions and hence minimizing the operational implications of the disturbance. In addition, the developed controls support enhanced scalability in the future grid given the autonomy of the approaches.

- *Balancing and frequency control with focus on FCC, BRC, and BSC use case combination*
  Investigating the results from the BSC perspective one realises that this use case manages an effective negotiation and, in addition, the system is benefited from the imbalance netting effect of two adjacent cells without jeopardising the stability in all simulation scenarios as well as in the experimental implementation. The negotiation is always successful even in the case of unequal imbalances or exhaustion of one tie-line’s capacity. Moreover, in all implemented scenarios the BRC controller deactivates the output power of the reserves, thus benefiting from imbalance netting exploitation. In all cases, the frequency stability is maintained, and overall, the frequency dynamics are limited proving that the combination of the proposed controllers is secure for the system operation. This is true even in the case of significant time delays such as in the simulation scenarios or the experimental implementation. The only issue identified during the tests was the unsuccessful restoration of the power of each individual tie-line. However, this issue is related to the absence of a voltage control strategy from the scenario that would control the power flow on the grid lines. This controller was deemed out of scope for this combination of the use cases and, therefore, is a potential scenario for further analysis.

  In terms of FCC and BRC effectivity in all scenarios the two controllers were capable of identifying the location of imbalances and acting towards successful frequency containment and frequency/balance restoration respectively. The presence of adaptive FCC always slightly worsens the dynamic frequency deviation; this could probably be something attributed to the non-optimized design of the fuzzy controllers. Otherwise, the controller effectively modifies the droop slope of all FCC reserves in order to increase the contribution of the faulty cell and decrease that of its neighbours.

- *Balancing and frequency control with focus on IRPC and FCC use case combination*
  The ability of FCC to improve short-term frequency stability of the investigated networks has been shown. Implementations of FCC in simulation and hardware implementation showed improvements of frequency nadir and steady state frequency deviation after a disturbance. In addition, the ability of an adaptive FCC to improve frequency stability metrics was proven. The higher frequency deviation in case of an adaptive FCC was found to be rather small, but with the advantage of less FCC contribution from reserves, which are located in cells, where no disturbance has happened.

  Furthermore, the ability of IRPC to improve RoCoF/inertia time constant of the overall grid has been presented through simulations. In experimental validation the positive impact of IRPC was not obvious. Reason for this is the chosen droop slope and deadband. These parameters are very important and need to be designed according to the ability of the chosen devices and the power system requirements.

Anyway, in a future power system with reduced inertia a contribution from other Distributed Energy Resources (DER) is needed. Other implementations to provide inertia, like virtual synchronous machines, need to be understood, integrated and validated in further investigations.

If the overall system inertia is decreasing to a very small value, distributed devices need to provide more inertia by activation of IRPC reserves. Therefore, more balancing energy is needed from distributed resources and the peak power injection needs to be higher. This could have negative impact on mechanical loads (wind turbines) or life-cycle of batteries. For this reason, overall system inertia should remain over a minimum in order to guarantee power system stability. Investigations in ELECTREA showed that the combination of FCC and IRPC and their distributed reserves contribute sufficiently to balancing control and improve the short-term frequency stability of a future power system.

- *Voltage control with focus on PVC and PPVC use case combination*
  From the realized experiments on the PVC and PPVC combination with several generation and load scenarios as well as cell configurations some general remarks can be highlighted. The implementation of a PVC/PPVC scheme in the WoC is advantageous from the perspective of the power losses reduction if compared with traditional planning schemes as it is based on the use of optimal power flows due to the observability capacities of the WoC. It also shows a faster recovery in case of an unexpected event as the system is able to restore the voltages to the optimal values in very short time frames. Additionally, it is beneficial in terms of a reduction in the number of activations of the PPVC. From the voltage control perspective, there is no real-time coordination between the neighbouring cells but only common agreements in terms of reactive power exchanges in the tie-lines. That means that, while ensuring enough reactive power reserves within the cell to reach an optimal power flow solution in the system, it is going to work properly. However, the possible conflicts between voltage and frequency controllers has not been explored and remains as future work to be accomplished.

4.4 Web-of-Cells and the market

As a complement to the new grid operation concepts proposed in ELECTRA, a high-level market design supporting the functioning of the architecture for frequency and voltage control developed within the Web-of-Cells (WoC) power grid structure is outlined in the following paragraphs. Particular emphasis has been put on the market mechanisms and conditions required to perform trading in balancing and voltage control products and to establish the final Merit Order lists, linked to the Merit Order Collection (MOC) and the Merit Order Decision (MOD) functions of the proposed control mechanisms.

An integrated approach has been considered combining the concepts of market and its objectives, principles of market functioning, reference model, market design elements and market assessment criteria.

4.4.1 Market

Within the WoC control architecture the market is an organized marketplace where the Cell System Operator (CSO) and the Balance and Voltage Control Service Providers (BSPs) meet to trade balancing and voltage control products.

Marketplace description

An **organized marketplace** is established. This is a multilateral system, which brings together or facilitates bringing together many buying and selling interests in products in a way that results in a contract. In such a system there is no obligation for the BSPs to offer balancing and voltage control products in the market. On the contrary, the BSPs voluntarily participate in the market and bid a volume and price at which are ready to sell. The pursuit of transparency, confidentiality, anonymity and publicity are all relevant reasons for the selection of an organized marketplace for trading balancing and voltage control products. The drawback of the market model is high data management costs and availability to facilitate the exercise of market power if several large-scale BSPs take part in the market.

Exchange as a type of organized marketplace is established because it creates preconditions to increase competition through the determination of clear, transparent and non-discriminating trading rules. It operates much faster than bilateral markets, because the CSO and BSPs do not specify any contract terms they desire. In the exchange standard balancing and voltage control products are traded, meaning that contracts are uniform in regard to their structure and form. This enables the CSO to compare identical balancing and voltage control products and activate the most cost-efficient solution. Standardized balancing and voltage control products support the integration of Renewable Energy Sources (RES), Distributed Energy Resources (DER) and storage technologies into the market. Due date, place of delivery, the time in which the deliveries take place and the conditions for clearing and settlement are standardized in the exchange too. The set of rules such as the conditions to be admitted to trade on the exchange are made public and are the same for every BSP. Prices and revenues are made public too and these allow the BSPs evaluating the position of their bids on the Merit Order list relative to bids from other BSPs. The participation is voluntary and non-discriminatory. Trading partners do not have to be found and the counterparty risk is minimized. Since the trading process is anonymous, the BSPs keep their strategy in a secret. In addition, the process to offer flexibility in the market is easy with a low entry barrier.

Auction as an instrument to promote competition in procurement of balancing and voltage control products, as an institution to determine the price and to conduct the trade in the exchange, and as the economic mechanism to allocate the balancing and voltage control products in economically efficient way is used.

Closed-type auction design is chosen. In this type of the auction, the BSPs privately submit their bids and offers to the CSO. The CSO keeps this information private, such that there is no sharing of bidding information amongst the BSPs. The BSPs are informed whether they won or lost. It is expected that limiting the provision of information works as a constraint on exercising market power and thereby increasing prices of balancing and voltage control products.

Multi-unit auction design is selected since it is in line with the roles that are set for the market of balancing and voltage control products, particularly, establishing competitive situations in the market, increasing utilization efficiency, increasing price efficiency.

Uniform auction design is applied. Subject to the uniform auction, the CSO collects all the bids and offers from the BSPs, creates an aggregate supply curve for the balancing and voltage control products, and match it with the requested volume of these products. The CSO establishes the Market-Clearing Price (MCP). Win the BSPs whose bids, or sections of their bids, offer lower price than or equal price to the MCP. All winners receive the same price (“pay-as-clear”), independently on their bids and offers.

Both **one-sided** and **two-sided auctions** are organized. One-sided auction is established subject to intra-cell trade in balancing and voltage control products, while two-sided auction is used subject to inter-cell trade in products. Thus, one-sided auction is used to trade in the IRPC, aFCC, BRC and PPVC services and two-sided auction is used to trade in the BSC service. The peculiarity of the one-sided auction is that the BSPs bid price and volume of the balancing and voltage control product which they are ready to trade through the auction. Since the CSO is a single buyer and can dampen the price, which then could be too low for the BSPs to participate in the market for balancing and voltage control products, the CSO bid only volume but not a price in the auction. In two-sided auction many CSOs participate in the market, therefore bidding of price and volume of balancing control product (in particular, the BSC service) is allowed.

Market actors

The Balance and Voltage Control Service Providers (BSPs), the Balance Responsible Parties (BRPs), the Cell System Operators (CSOs) and the Regulatory Authority (RA) are four main types of actors acting at the procurement and the settlement sides of the market for balancing and voltage control products within the WoC power grid structure.

The **Cell System Operator** (CSO) is a market actor procuring balancing and voltage control products from the BSPs to balance electricity consumption and production in real-time and supplying them to the BRPs who are in imbalance. The CSO is responsible for the secure operation of the cell, the procurement of the balancing and voltage control products for its cell, and to ensure the electricity supply in a safe, efficient and reliable manner. In relation to the market for balancing and voltage control products, the CSO is responsible for the preparation of market regulations and technical regulations.

The **Balance and Voltage Control Service Provider** (BSP) is a market actor selling balancing and voltage control products to the CSO. They sell reactive power, capacity for inertia, inertia, balancing capacity and balancing energy for upward or downward regulation to the CSO. A list of the BSPs able to supply the CSO with balancing and voltage control products is given in Figure 8.

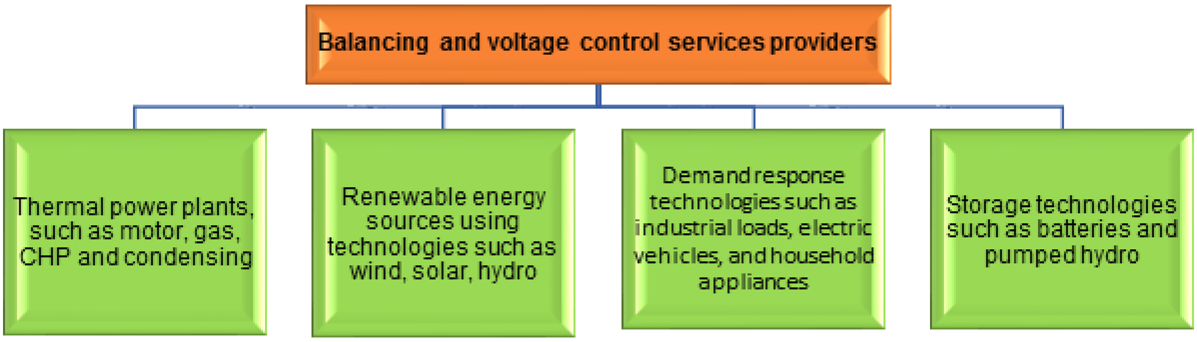


Figure 8: List of BSPs sellers of balancing and voltage control products

The **Balance Responsible Party** (BRP) is a market actor responsible for its imbalances. The roles and responsibilities of the BRPs in the market for balancing and voltage control products are in line with the requirements determined in [8]:

- In real-time, each BRP strives to be balanced or help the power system to be balanced.
- Each BRP is financially responsible for the imbalances to be settled with the CSO.
- Prior to the Intraday Cross-Zonal Gate Closure Time (ICZGCT), each BRP may change the schedules required to calculate its position.
- After the ICZGCT, each BRP may change the internal commercial schedules required to calculate its position.

The **Regulatory Authority** (RA) is an independent regulatory body mandated, according to its competence, to perform the regulatory functions in the electricity and renewable energy sectors in the cells to ensure a proper implementation, supervision and control of the regulated electricity and renewable energy activities, rights and responsibilities of energy companies and consumers, as well as to ensure a fair competition in the electricity sector. The RA role in the electricity and renewable energy activities is important, since the RA is responsible for the stable regulatory framework that facilitates the necessary investments in new generating capacity and networks, thereby contributing to security of supply.

Balancing and voltage control products

Within the WoC power grid structure, new kinds of balancing and voltage control products are developed and traded in the market (Figures 9-10).

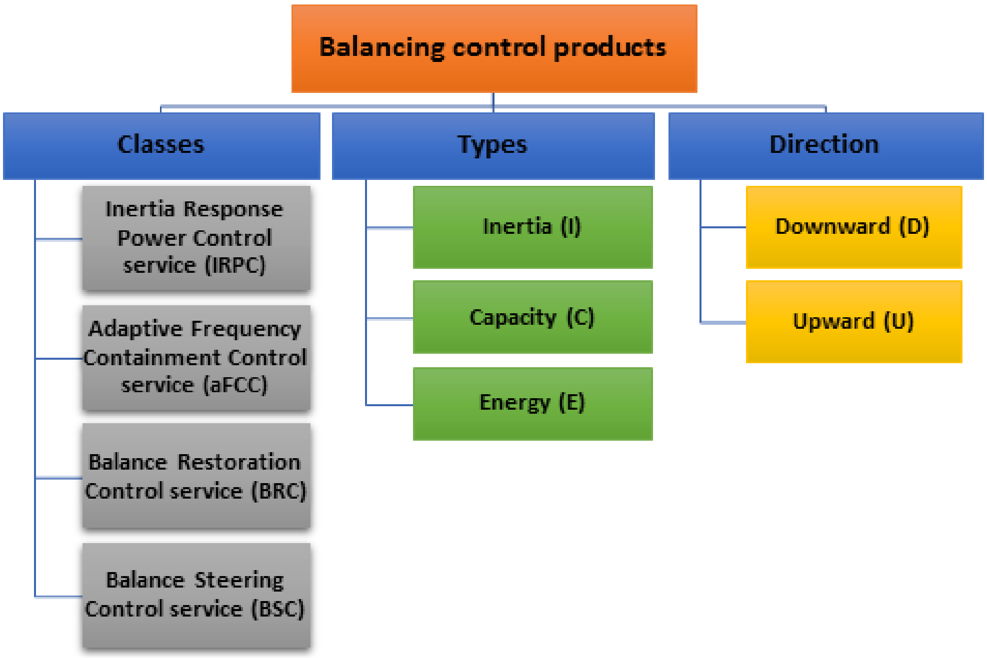


Figure 9: Categorization of balancing control products

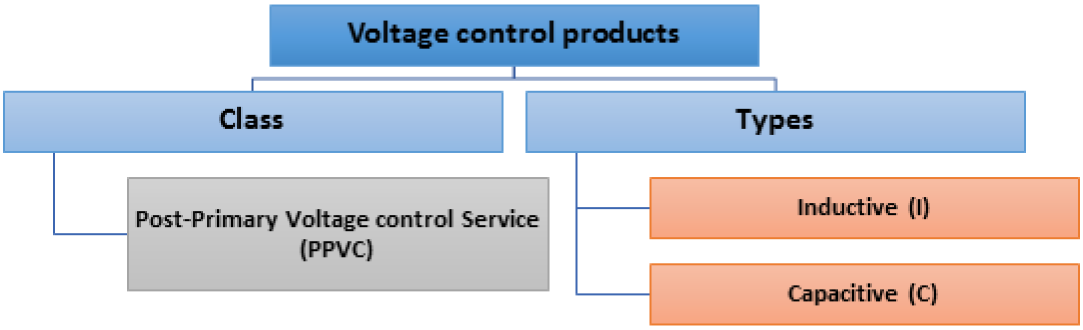


Figure 10: Categorization of voltage control products

The classes of balancing control products are the services for *Inertia Response Power Control (IRPC)*, *Adaptive Frequency Containment Control (aFCC)*, *Balance Restoration Control (BRC),* and *Balance Steering Control (BSC)*. For these services four types of balancing products are traded:

- Capacity for inertia means a volume of reserve capacity that the BSP has agreed to hold and in respect to which the BSP has agreed to submit bids for a corresponding volume of inertia to the CSO for the duration of the contract.
- Inertia means inertia used by the CSO and provided by the BSPs.
- Balancing energy means energy provided by the BSPs, either injected or withdrawn, used by the CSO to perform balancing (to compensate for unforeseen imbalances and to guarantee the stability of the power system).

- Balancing capacity means a volume of reserve capacity that the BSP has agreed to hold and in respect to which the BSP has agreed to submit bids for a corresponding volume of balancing energy to the CSO for the duration of the contract. Balancing capacity is procured by the CSO ahead of real-time with the purpose to hedge the CSO against the risk of not having enough balancing energy bids by the BSPs in real-time.

Two directions of balancing products (except inertia) are available:

- Upward regulation means an increase in generation (or decrease in consumption).
- Downward regulation means a decrease in generation (or increase in consumption).

Two classes of voltage control service are developed within the WoC power grid structure, however, only one class is developed as a product for trading purposes. This is:

- Post-Primary Voltage Control (PPVC) service is the commitment to keep or bring the voltage levels in the nodes of the cell back to the safe-band values, while optimizing the power flows in order to minimize the losses in the network. Each cell is responsible for its own voltage control.

Two types of voltage control products are developed: consumption and injection of reactive power:

- Inductive reactive power is used when voltage is too high to compensate the capacitive reactive power.
- Capacitive reactive power is used when voltage is too low to compensate inductive reactive power.

Standard balancing and voltage control products are traded in the WoC power grid structure with the minimum requirements shown in Table 1.

Table 1: Requirements for the standard products

Characteristic	IRPC	aFCC	BRC	BSC	PPVC
Ramping period	<1 MW×s/s	<1 MW/s	<10 MW/min	Same with BRC	<5 MVA/min
Full activation time	<1 s	2-5 s	10-30 s	10-30 s	30 s
Minimum and maximum quantity	<1 MW×s	< 1 MW	1-5 MW	1-5 MW	5-10 MVA
Preparation period	<1 s	<5 s	<1 min	<1 min	<5 min
Deactivation period	<20 s	10-30 s	10-30 s	10-30 s	10-30 s
Minimum and maximum duration of delivery period	15-60 min				
Validity period	15 min	15 min	15 min	15 min	120 s
Mode of activation	Merit order	Merit order	Merit order	Merit order	Optimal power flow calculation

4.4.2 Designing of market elements

A set of general, balance planning, product provision and imbalance settlement market design elements is considered within the WoC power grid structure (Figure 11).

General elements	Balance planning elements	Product provision elements	Imbalance settlement elements
Bid Time Unit;	Zonal vs. nodal responsibility;	Procurement scheme;	Imbalance settlement period;
Publication of Cell information.	Balance obligation;	Pricing mechanisms;	Types of imbalances;
	Balancing scheme;	Cascading procurement;	Imbalance pricing mechanisms;
	Net vs. separate positions;	Remuneration scheme;	Imbalance price;
	Notification of energy schedules	Activation scheme;	Method for determination of imbalance price;
	Initial gate closure time.	Timing of market for balancing and voltage control products.	Allocation of costs;
			Penalty for non-delivery
			Timing of settlements.

Figure 11: Levels of principles to develop a market design for balancing and voltage control products

General elements

Within the WoC power grid structure the Bid Time Unit (BTU), which is the main time unit in the market for balancing and voltage control products dividing the balance responsibility between the CSO and the BSPs, is linked to Schedule Time Unit (STU), dividing responsibility between the CSO and the BRPs, and Imbalance Settlement Period (ISP), the period for which imbalance of the BRP is calculated. It is expected that linking the BTU to STU and ISP will improve operational and price efficiency. Moreover, to improve balance planning accuracy, availability of balancing resources and price efficiency, a short BTU, STU and ISP (of 15 minutes) instead of long (of 60 minutes) is proposed.

With the purpose to develop a transparent market for balancing and voltage control products, publication of information is of high importance. A high-level framework of a transparent market for balancing and voltage control products is proposed. It is developed in a way to assure horizontal and vertical transparency of the market for balancing and voltage control products.

Balance planning elements

Within a WoC, producers, consumers and traders of electricity have a balance obligation. Electricity produced from RES participate fully in the balancing mechanisms. This means that they have the same responsibilities as other type generators, and are allowed to provide balancing resources subject to common rules. With the purpose to assure very accurate accounting of imbalance, a unit-by-unit balancing scheme is applied for large units, but a portfolio balancing scheme allowing aggregations of units is used in case small-scale RES. The BRPs submit separate energy schedules for production, consumption and trade (import and export) during the predefined time periods. The Initial Gate Closure Time (IGCT) at which the BRPs must submit general initial energy schedule to the CSO is related to the time period from the day-ahead (DA) market closure to the intraday (ID) market opening, but particular time should be selected following the criterion of reasonableness meaning that the BRPs have sufficient time to prepare the initial energy schedules and the CSOs has enough time to aggregate them and take decision regarding volume of balancing and voltage control product is required for the cell.

Balance and voltage control products provision elements

The CSO procures the balancing and voltage control products in the organized market, which is an auction-based exchange. The market considers a uniform pricing rule for balancing and voltage control product price setting. Under the uniform pricing rule, the BSPs who won the auction are paid a single price, which is the Market-Clearing Price (MCP) regardless of their bids. Cascading procurement principle, which is expected that will increase price efficiency in the market for balancing and voltage control products, is implemented. The implementation of the principle means that any surplus of high-quality balancing product is by the auctioneer (CSO), automatically transferred to the market for lower-quality balancing product and so on. Balancing and voltage control products are procured on commercial basis and the BSPs are remunerated for the provision of these products. The CSOs pay the BSPs for the inertia capacity and balancing capacity availability and for their utilization, if the IRPC, aFCC, BRC and BSC services are activated in real-time. PPVC service is paid if reactive power is used in real-time. Each CSO shall use cost-effective balancing energy bids available for delivery in its cell based on the merit order list. Inertia is activated based on a merit order list principle, and reactive power based on an Optimal Power Flow (OPF) calculation (for which a merit order list could be considered as well).

Imbalance settlement elements

Within the WoC power grid structure's imbalance settlement model, each CSO calculates the final position, allocated volume and imbalance for each BRP, for each ISP and in each imbalance area (cell). Final position of the BRP is calculated using the approach that the BRP has three final positions – production, trade, and consumption. The WoC power grid structure supports the single pricing mechanism for imbalance price setting because it assumes that there should be no imbalance pricing asymmetries, meaning that there should be no different prices paid for being positive or negative imbalance within a given settlement period. Moreover, the WoC power grid structure keeps an idea that a single pricing should be applied to all types of imbalances. For the reason of transparency, clearness and simplicity, the balance incentivizing components that sometimes are added to the regulation prices to punish the BRP imbalances in the same direction as the system imbalance or to incentivize all BRPs to keep their balance, are not foreseen within the WoC. It is expected that the single pricing will lead to the lowest actual imbalance cost and will result in the highest cost allocation efficiency. It will not discriminate against small market actors. However, this mechanism could give weaker incentives for balance planning accuracy. An imbalance price is calculated based on the MCP of upward and downward regulation.

4.4.3 Market design

The market for balancing and voltage control products is a constituent part of the wholesale electricity market. In addition to the capacity markets for the procurement of reserves (balancing and voltage control services) to be activated if necessary in each cell during the real-time operation by the CSO, the set-points of all cells will be established through energy-only markets.

In a day-ahead market (DA), which is established at the WoC level, electricity is traded one day before the actual delivery. The cell has to be in balance at the end of the DA market (i.e., scheduled generation in the cell shall be equal to the forecasted demand in the cell plus net export to another cell). Electricity is traded both the day-ahead bilaterally (OTC trading) and on the day-ahead power exchange, as it is today.

In the intra-day market (ID), which is established at the WoC level, electricity is traded on the delivery day itself. The ID market enables market actors to correct for shifts in their DA nominations due to better wind forecasts, unexpected power plant outages, etc. This is a continuous market, and trading takes place every day until one hour before delivery.

The Market Operator (MO) provides the results of the energy-only markets (bilateral, DA and ID markets) to each CSO – such as production and consumption volumes of the cell, tie-lines power flows and electricity prices – who then estimates the total balance in the cell and based on the estimations, necessary “set-points” are set for each cell.

In the energy balancing markets, energy bids are collected in merit order list at the regional level between neighbouring cells, which enables CSOs to correct possible power system imbalances before RT, closer to defined “set-points” after ID market closure; collection of energy bids is accepted until 15 min. before the production hour.

The CSOs maintain the system balance by activating balancing capacity. The balancing capacity market is not part of the pure energy-only market, since balancing capacity delivers both energy services (i.e., generating electric energy when activated) and capacity services (i.e., reserving generation capacity). The CSO is the single buyer of balancing capacity and contracts different types of balancing capacity.

In the market for balancing and voltage control products, capacity for inertia, balancing capacity, inertia, balancing energy and reactive power is traded between the BSPs and CSOs at the intra-cell and inter-cell levels and settlements between the CSOs and the BRPs are carried out. As such, the market for balancing and voltage control products is split into a procurement side (i.e., procurement and activation of balancing and inertia capacities (if necessary, in real-time), as well as reactive power by the CSOs) and a settlement side (i.e., financial settlement of the BRP imbalances by the CSOs).

At the procurement side of the market for balancing and voltage control products the BSPs sell IRPC, aFCC, BRC, BSC and PPVC services and the CSOs procure them. Each balancing and voltage control product is traded in a separate sub-market (Figure 12). The sub-markets for inertia capacity, inertia, balancing capacity and balancing energy for upward and downward regulation, inductive and capacitive reactive power are established too. For each balancing product there are established two main types of sub-markets: balancing capacity (the BSPs are compensated for availability of reserves) and balancing energy (the BSPs are compensated for the actual delivery of electricity (i.e. utilization of balancing capacity), or inertia capacity and inertia. In the sub-market for voltage control products reactive power is traded. Since voltage is a very local problem, therefore it is solved locally by local voltage service providers. It is expected that at least several voltage control service providers capable to locally solve voltage problems will be available in future.

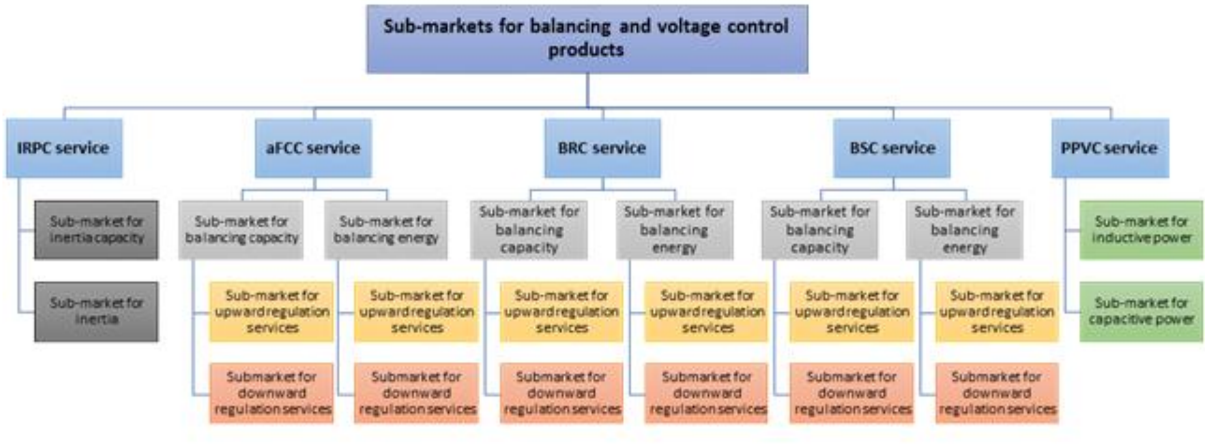
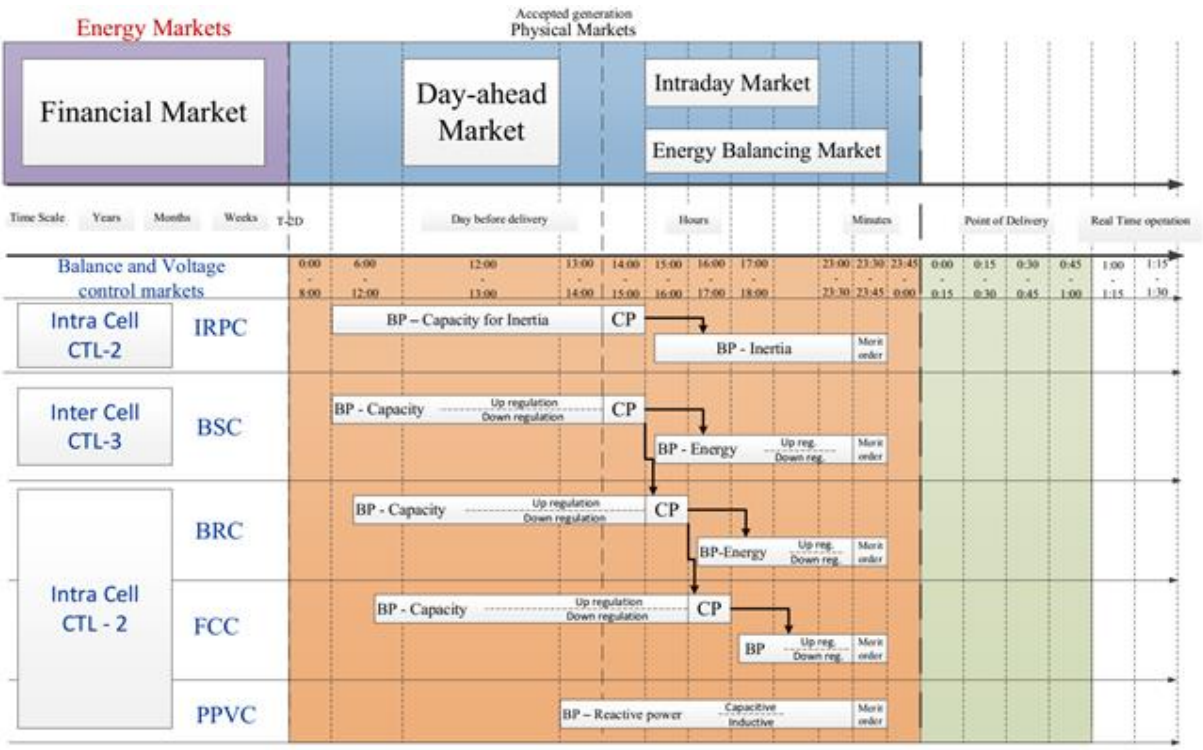


Figure 12: Sub-markets for balancing and voltage control products

The CSO has the responsibility to balance the cell (stick to the cell set-point) by using available resources to maintain the frequency and voltage and to secure a stable operation. The CSO will compensate cell imbalances in real-time by activating balancing capacities, which are contracted ahead of time from the market actors who provide balancing and voltage control products (BSPs). At the settlement side, the CSOs sell balancing and voltage control products to the BRPs who are in imbalance, and the BRPs pay for the provision of products. The BRP's imbalance is the quarter-hourly (15 min.) difference between the BRP's total injections and off-takes. The total imbalance in the cell is the sum of all BRP imbalances.

The timing of sub-markets for balancing and voltage control products is organized in a way that initially, the BSPs decide on in which sub-market – inertia capacity or balancing capacity – they take part in (Figure 13).



Note: BP – bidding process; CP – clearance process.

Figure 13: Timing of sub-markets for balancing and voltage control products and t

Those BSPs who decide to participate in the sub-market for inertia capacity and whose bids are accepted for a particular market time unit, are not allowed participating in other sub-markets for this market time unit. The same is valid for the BSPs who bid the balancing capacity. Those BSPs who decided to participate in the sub-market for balancing capacity for a particular service and whose bids are accepted for a particular market time unit, are not allowed participating in other sub-markets, except in the sub-market for balancing energy. Moreover, those BSPs whose bids of higher quality balancing capacity are rejected by the market can bid the sub-market for lower-quality balancing capacity or bid the sub-market for voltage control services, if they satisfy bidding requirements. The sub-markets for inertia capacity and balancing capacity are organized earlier than sub-markets for inertia and balancing energy, since inertia and balancing energy bids are submitted to the market by the BSPs who won inertia capacity and balancing capacity auction and thus have the obligation to keep the inertia capacity or balancing capacity for the particular market time unit. Thus, a clear interrelationship of the timing of sub-markets is established. The timing of sub-markets for reactive power is organized in a way that merit order is established. According to the current specification of PPVC, no merit order function is considered. Activation is based on real-time OPF which considers as an initial assumption that all resources have the same price (market-resulting merit order list could be considered as well, if necessary).

In the market, the balancing and voltage control products are traded between the BSPs and CSOs at intra-cell and inter-cell levels, and settlements are carried out between the CSOs and the BRPs. The interactions between these market actors split the market into a procurement side and a settlement side (Figure 14).

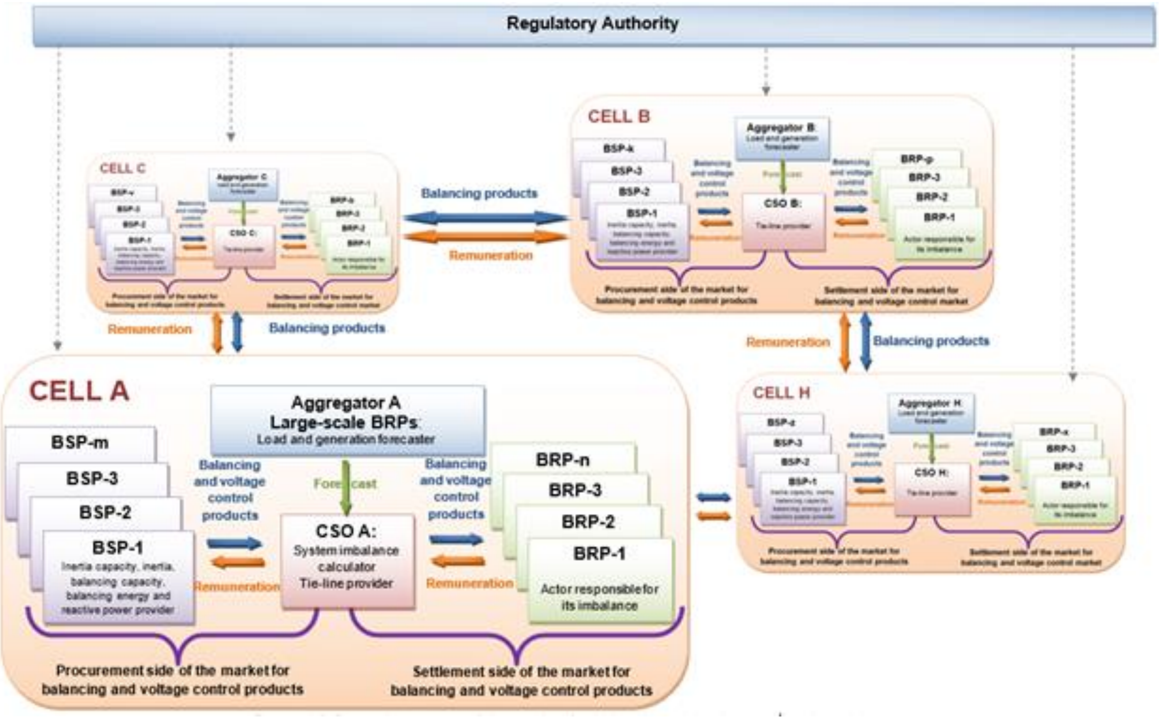


Figure 14: Interactions of the market actors for balancing and voltage control services

4.5 Roles and responsibilities

A cell is managed by a so-called **Cell System Operator (CSO)**. The CSO role can be interpreted by the traditional DSOs or TSOs (distribution or transmission 'Cell Operators') or by new types system operators, that can be defined by regulation authorities.

As a physical entity, a Cell System Operator can be responsible for many cells respectively cell controllers on the basis of providing more optimal (financially and technically) solutions to the integrated grid. This does not change the real physical structure of cells and its physical constituents. Each CSO is responsible for establishing and maintaining automatic control mechanisms as well as procuring sufficient reserves, contributing to a stable and secure system operation. This is done by:

- Contribution to containing and restoring system frequency and a secured power exchange by maintaining the cell balance under operating schedules by timely activation of local reserves (by means of IRPC, BRC, aFCC, BSC mechanisms).
- Containing, stabilizing and restoring local voltage within safe boundaries (by means of PPVC mechanism).
- Operating in real-time the state of a cell. A CSO has the role of monitoring the system and its interconnections (tie-lines), to initiate control actions in response to critical events in order to maintain secure and stable operation. Further, it is the CSO's responsibility to coordinate with neighbouring operators regarding control actions that affect them as well (mainly by means of BSC mechanism).

The CSO is responsible for the procurement of capacity reserves in the appropriate markets of balancing and voltage control services. The CSO will buy inertia capacity, balancing capacity and reactive power products from Balance Service Providers (BSPs), and will activate them in real-time when necessary (cell imbalance or voltage problem).

Each CSO procures balancing services via an organised marketplace (exchange, where harmonized trading rules are applied), using a common platform developed at the WoC level, and which employs an auction as a mechanism for efficient allocation of resources and efficient pricing of inertia, balancing and voltage control services. The auction is cleared based on price of bids submitted by the BSPs to the capacity markets open separately for each cell by the corresponding CSO. A market clearing price (MCP) for all BSPs in the cell is established. Based on the MCP, the CSO will remunerate BSPs for availability of capacity for inertia, balancing capacity, and reactive power capacity, and for their utilization in real-time if needed.

The CSO must also generate the necessary information for establishing the set-points of the cells in the energy-only markets (day-ahead and intraday), and to calculate the needed reserves (inertia, balancing capacity and reactive power) for the cell. In addition to the cell tie-lines constraints, this information includes the cell generation and load forecasts/schedules provided to the CSO by Balance Responsible Parties (BRPs) and Aggregators.

After receiving energy schedules, the particular CSO aggregates the BRPs production, consumption, tie-lines power flows and trade energy schedules at cell level and derives the net position of the cell.

During the real-time operation of the cell, the CSO activates the balancing energy, inertia and reactive power reserves, if needed. The CSO recovers the cost of these services provision from the BRPs who were in imbalance during the particular market time unit, i.e. the CSO sells the procured balancing and voltage control products to the BRPs who are in imbalance. The CSO settles these individual imbalances with the BRPs by applying imbalance prices to their imbalance positions. The BRP's imbalance is the quarter-hourly (15 min) difference between the BRP's total injections and off-takes. The total imbalance in the cell is the sum of all BRP imbalances.

In relation to the market for balancing and voltage control products, the CSO is responsible for the preparation of market regulations to the BSPs and the BRPs. Market regulations are established to regulate the rights and obligations of the BSPs and the BRPs in the market, and to ensure that the market for balancing and voltage control products will function properly and that settlement will be performed correctly.

A **Balance and Voltage Control Service Provider (BSP)** is an actor selling balancing and voltage control products to the CSO in the procurement phase of capacity markets. Balancing and voltage control products are provided by the BSPs to the CSO by bidding in an organized market. There is no contract or obligation for the BSPs to offer in the market, inertia, capacity for inertia, reactive power, balancing capacity, and balancing energy for upward or downward regulation; the BSPs voluntarily participate in the market and bid a volume and price at which would wish to sell to the CSO. Through this bidding process, the BSPs establish the supply curves of the capacity markets.

Besides, balancing and voltage control products can be acquired by the CSOs in the bilateral market, when the BSPs and the CSO negotiate a contract regarding the offered balancing and voltage control product (its quantity and quality) and its price. Bilateral contracts are valuable since they protect the BSPs and the CSOs against price uncertainty and make revenue and payment streams more predictable.

BSPs are compensated for availability of balancing capacity, and for the utilization, when necessary, of that capacity by the CSO during the real-time operation of the cell (actual delivery of electricity).

The rights and responsibilities of the BSP in the market for balancing and voltage control products are the following:

- The BSP qualifies for providing bids for balancing energy or balancing capacity which are procured and activated by the CSO.
- Each BSP participating in the procurement process for balancing capacity submits and have the right to update its balancing capacity bids before the gate closure time (GCT) of the bidding process.
- Each BSP with a contract for balancing capacity submits to its CSO the balancing energy bids corresponding to the volume, products, and other requirements set out in the balancing capacity contract.
- Any BSP has the right to submit to the CSO the balancing energy bids from the standard products for which it has passed the prequalification process.

The distributed generation and renewable energy sources (producers-consumers-prosumers) usually do not have the minimum participation size to enter as individuals in the markets for provision of ancillary services. Sometimes, the distributed generation units do not even have enough control capabilities to be able to adapt their operating mode according to the needs.

An **Aggregator** is an entity, that gathers the flexibility by forming Virtual Power Plants (VPPs), that will enable the participation of those smaller units in the balancing and voltage control services markets. It is a type of BSP. The same concept can be used also for the Aggregator as a type of BRP.

A **Balance Responsible Party (BRP)** is an actor with a valid balance agreement with the CSO, and manages a balance obligation on its own behalf as a producer (conventional or RES-based), consumer or trader of electricity, or on the behalf of other producers, consumers or traders of electricity.

During the stage of balance planning the BRPs are obliged to provide to the CSO the planned energy production, consumption and trade schedules (separately) for every Schedule Time Unit (STU) within the day of delivery. Moreover, energy schedules for import and export shall be notified to the CSO separately too as the trade directions (into the cell and from the cell) are understood to be equivalent to production and consumption, respectively.

The BRP is responsible for its imbalances. Imbalance means an energy volume calculated for the BRP and representing the difference between the allocated volume attributed to that BRP and the final position of that BRP within a given imbalance settlement period (assumed to be 15 min in the WoC). An imbalance indicates the size and the direction of the settlement between the BRP and CSO. An imbalance can be positive meaning that the BRP is in surplus of electricity, or negative meaning that the BRP is in shortage of electricity.

The rights and responsibilities of the BRPs in the market for frequency and voltage control products are the following:

- In real-time, each BRP strives to be balanced or help the power system to be balanced.
- Each BRP is financially responsible for the imbalances to be settled with the CSO.
- Prior to the intraday Gate Closure Time, each BRP may change the schedules required to calculate its position.
- After the intraday Gate Closure Time, each BRP may change the internal commercial schedules required to calculate its position.

The **Market Operator (MO)** is the entity responsible to favour the transparent operation of the market and to bring together all the interests of multiple actors buying and selling products in a non-discriminatory way. The MO provides the results of the energy-only markets (bilateral, DA and ID markets) to each CSO – such as production and consumption volumes of the cell, tie-lines power flows and electricity prices – who then estimates the total balance in the cell and based on the estimations, necessary “set-points” are set for each cell.

5 Transferring the WoC approach into the present power systems

As indicated above (see Section 1.2), as planned, the technology readiness level (TRL) of ELECTRA IRP outcomes reaches 3 to 4, being TRL4 “Prototype or component validation under laboratory conditions”. TRL5 and beyond are for pre-commercialization and testing of prototypes under real or field conditions, and are clearly beyond the ELECTRA scope. The developments around the WoC concept within ELECTRA were focusing on flexible (aggregate) resource level (control topology level CTL 1), cell level (CTL 2) and inter-cell level (CTL3). The physical, single device level (CTL 0) was not in scope of the research, considering the long-term research perspective (2030+) as well as the conceptual RTD work performed. Nevertheless, it was requested to partly address the device level, when setting up the test cases and performing the individual lab-scale experiments.

For increasing the TRL of the WoC concept and enabling the implementation and application in real networks, effort on device level as well as on the actual communication interfaces and protocols is requested, in order to ensure the provision of the required flexibility for the different use cases and underlying functionalities in real environment. This includes flexible and adaptive set of active grid components capable of efficiently delivering the quality of supply specified by grid rules and/or grid codes, irrespective of size or position (central or regional). Before applying the WoC in real networks, it is needed to further detail and refine the concepts as well as to analyse and verify them, taking into consideration the implementation of the functionalities (algorithms) at device level in particular. Since corresponding proof of concept tests have been carried out with some limitations further research and development on higher TRL levels is necessary, including more concrete rules for defining cells and corresponding test networks and benchmark criteria.

The WoC concept as well as the related control function are addressing the power system 2030+. One important assumption of ELECTRA is that developments in Information and Communication Technologies support the pathway towards more decentralized managed power systems. The analysis of communication standards in light of the ELECTRA use cases included the definition of the information and communication layers of their Smart Grid Reference Architecture (SGAM) modelling (starting from the function layer and making hypotheses on the component one). The analysis gave very good results putting in evidence that the information exchange needed by the ELECTRA use cases are completely covered by the existing standards. Since there was again no focus on device level, before implementing and applying the WoC concept in present networks these issues need to be clarified as it is true for any remotely-controlled device going to be integrated in the real system.

Another important aspect in terms of WoC application is the issue of integrating the concept in the processes as well as the control room functionalities of power system operators. ELECTRA IRP developed a high-level design of an overarching architecture for future control room functionality in a WoC context. In order to demonstrate an integrated decision support system, a design for the combination and co-ordination of the developed decision support tools has been created, including how they react to decision points and events. This decision support system blueprint for different control functionalities can fully support the control of the WoC concept, and allows the human operator to benefit from improved information and automated decision making under complex WoC scenarios. In addition, a number of visualisation prototypes have been developed for different decision support control functions. These provide operators with key information, and provide situational awareness during events. They also allow operators to access network data and to alter or add control actions if necessary. For an implementation of the WoC in real grids, these prototypes need to be further refined, commercialised and integrated in actual SCADA systems presently in use.

The increase of the ELECTRA WoC concept TRL, including the clarification of the above mentioned issues at device level, are a key requirement for performing detailed scalability analysis of the related technologies in the existing grid supporting the provision of a detailed implementation migration plan in the future.

From a regulatory perspective, the management of BSC requires the definition of competitive and non-discriminatory mechanisms for tie-line constraint calculation, information exchange, activation and deactivation. Currently, there is no mechanism analogous to BSC, active within the same time frames as that defined in the WoC concept. An evolution of the Coordinated Balancing Area (CoBA) between neighbouring TSOs would be necessary. A set of standard products for Imbalance Netting will require a definition, based on sound economic principles, in order to ensure harmonisation within and across CoBAs.

The analysis of the Market Design Initiative of the Winter Package and ENTSO-E Network Codes for market design show that the WoC concept should respect the high-level EU regulations, which are related to the general principles regarding the operation of wholesale electricity markets, including market for system balancing products.

6 Conclusions

The need for a transition towards a new functional architecture is based on a number of scenario assumptions regarding the 2030+ power system. It is assumed that in the future power system, generation will shift from classical dispatchable units to intermittent renewables and CHP. As a consequence, a great part of the generation will shift from few large units to many smaller units. It is assumed that electricity consumption and therefore system loads will increase significantly. Electrical energy storage is expected to be a cost-effective solution for offering ancillary services that stabilize the system and fill the momentarily gap between system generation and system load. Next to this, it is presumed that the power system observability will increase due to more ubiquitous sensors. In addition to this, the large amounts of fast reacting distributed resources will be able to offer reserves capacity.

In the ELECTRA IRP proposal, the EU power grid is decomposed into a ***Web-of-Cells*** structure, where the cells are defined as a group of interconnected loads, distributed generators and storage units within well-defined grid boundaries corresponding to a physical portion of the grid and corresponding to a confined geographical area. Cells have adequate monitoring infrastructure installed, as well as local reserves capacity enabling them to (partially) resolve voltage and cell balancing problems locally. Each cell is managed by a cell system operator, who takes responsibility for the real-time reserves activation and dispatching in his cell. Inter-cell reserve exchanges and coordination is included for optimal system-wide management. In each cell, the Cell System Operator maintains an accurate view on the overall cell state, and dispatches reserves located in the cell in a secure manner based on his knowledge of the cell state. In principle, no global system state information is required for this. In this way, a ‘divide and conquer’ way of tackling voltage and balancing issues is implemented, and local problems are resolved locally in the cell in a fast and secure manner, limiting complexity and communication overhead. There is no need to expose local problems at global system level.

In the proposed Web-of-Cells based architecture, Cell System Operators are responsible to contribute to containing and restoring system frequency, as well as containing local voltage within secure and stable limits. For this purpose, proposals for frequency and voltage control within a Web-of-Cells system are developed, and given in Table 1 and Table 2 below. It must be noted that by moving to a cell-based architecture, different observables and control aims are required.

Table 2: Overview of frequency control use cases

Frequency Control	
Now	**2030+**
	Inertia Response Power Control
Frequency Containment Control	Frequency Containment Control
Frequency Restoration Control	Balance Restoration Control
Frequency Replacement Control	Balance Steering Control

Table 3: Overview of Voltage Control Use Cases

Voltage Control	
Now	**2030+**
Primary Voltage Control	Primary Voltage Control
Secondary Voltage Control	Post-Primary Voltage Control
Tertiary Voltage Control	

On a conceptual level, supported by simulations and lab-scale validation, it has been proven that the WoC concept is in principal feasible and allows to provide real-time frequency (balancing) and voltage services in the future power system. This includes the underlying control functions supporting the six ELECTRA use cases, the observability functions in the power system, as well as the control room visualisation and most important the integration in future markets and regulation. Anyway, further developments and in depth investigations are necessary to increase the WoC technology readiness level, in order to be able to do first demonstrations in real networks in course of follow up projects.

From a regulatory perspective, the management of BSC requires the definition of competitive and non-discriminatory mechanisms for tie-line constraint calculation, information exchange, activation and deactivation. An evolution of the Coordinated Balancing Area (CoBA) between neighbouring TSOs would be necessary. The WoC concept should respect the high-level EU regulations, which are related to the general principles regarding the operation of wholesale electricity markets, including market for system balancing products.

7 References

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Full list of Web-of-Cells related ELECTRA deliverables

D3.1 - Specification of Smart Grids high level functional architecture for frequency and voltage control

D3.2 - Market design supporting the Web-of-Cells control architecture

D3.3 - Analysis of necessary evolution of the regulatory framework to enable the Web-of-Cells development

D4.1 - Description of security concerns and proposed solutions for the frequency and voltage control system & Maturity model for smart grid risk assessment

D4.2 - Description of the detailed Functional Architecture of the Frequency and Voltage control solution(functional and information layer)

D4.3 - Existing standards and Gap analysis for the proposed frequency and voltage control solutions

D4.4 - ELECTRA Web-of-Cells Cyber Security Analysis Report

D5.2 - Functional description of the monitoring and observability detailed concepts for the Distributed Local Control Schemes

D5.4 - Functional description of the monitoring and observability detailed concepts for the Pan-European Control Schemes

D5.5 - Observables for the Web-of-Cells concept

D6.1 - Functional specification of the control functions for the control of flexibility across the different control boundaries

D6.2 - Impact of network disturbances on the proposed voltage and frequency control solution

D6.3 - Core functions of Web-of-Cells control scheme

D6.4 - Simulations based evaluation of the ELECTRA WoC solutions for voltage and balancing control – stand-alone use case simulation results

D7.1 - Report on the evaluation and validation of the ELECTRA WoC control

D7.2 - Lessons learned from the ELECTRA WoC control concept evaluation and recommendations for further testing and validation of 2030 integrated frequency and voltage control approaches

D8.1 - Demonstration of visualization techniques for the control room engineer in 2030

D8.2 - Demonstration of decision support for real time operation encompassing the identification of key threats and vulnerabilities and the provision of assessed interventions

D8.3 - Recommendations on future development of decisions support systems

8 Disclaimer

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