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ELECTRA

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

The Web-of Cells Concept

An architecture for decentralized balancing and voltage control in the future power system

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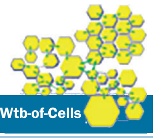
Executive Summary

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 combined heat and power plants. As a consequence, a great part of the generation will shift from few large units to many smaller units. It is also 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 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. Moreover, the large amounts of fast reacting distributed resources will be able to offer reserves capacity.

In the ELECTRA Integrated Research Program proposal, the EU power grid is decomposed into a **Web-of-Cells (WoC)** structure, where the cells are defined as 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. Cells have adequate monitoring infrastructure, as well as local reserves capacity enabling them to resolve voltage and cell balancing problems locally. Each cell is managed by a cell system operator, relying on a cell controller, who takes responsibility for the real-time reserves activation and dispatching in his cell(s). Inter-cell exchanges and coordination is included in order to benefit from imbalance netting. In each cell, the Cell System Operator maintains an accurate view on the overall cell state, and consequently dispatches reserves located in the cell in a secure manner. In principle, no global system state information is required for this. In this way, 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 WoC-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 were developed, and are given in Table 1. It must be noted that by moving to a cell-based architecture, different observables and control aims are required.

Table 1: Overview of frequency/balance and voltage control use cases

	CURRENT	Wtb-of-Cells
BALANCE FREQUENCY CONTROL	-	Inertia Steering Control
	Frequency Containment Control (FCC)	(Adaptive) Balance Restoration Control (BRC) (Adaptive) Frequency Restoration Control (aFCC)
	Frequency Restoration Control (FRC)	-
	-	Balance steering control (BSC)
VOLTAGE CONTROL	Primary Voltage Control	Primary Voltage Control
	Secondary Voltage Control Tertiary Voltage Control	Post-Primary Voltage Control (PPVC)

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 importantly, 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 balance steering control 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 between neighbouring transmission system operators would be necessary. Undoubtedly, the WoC concept must comply with 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.

Introduction

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. The aim is to correct real-time imbalances (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 (T0) and it addresses real-time deviations from 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. 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) centred manner. Instead, a new approach is required, that leverages innovative monitoring systems based on a fully instrumented network, and autonomous distributed control functions. In order to regain reliable control over the power grid, distributed generators and loads should and will be controlled to manage the continuous stream of imbalances as perceived system-wide by the TSO's today.

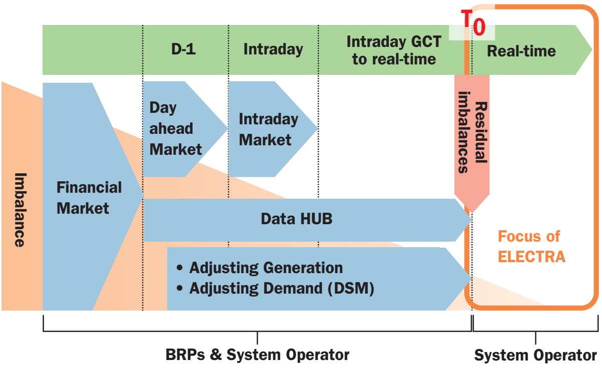


Figure 1: ELECTRA focus of balancing procedures

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) grid, to allow the TSO 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 approach, the so-called Web-of-Cells (WoC) concept [1] [2], which is described in this document. Since the ELECTRA IRP is targeting the time horizon 2030+ the WoC proof of concept validation was performed mainly by simulations and lab-based experiments.

The ELECTRA key assumptions

ELECTRA analysed control solutions are not related to a specific scenario, but instead related to a number of clear and indisputable trends, that fit multiple future scenarios. 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 [3] 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 2). 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.

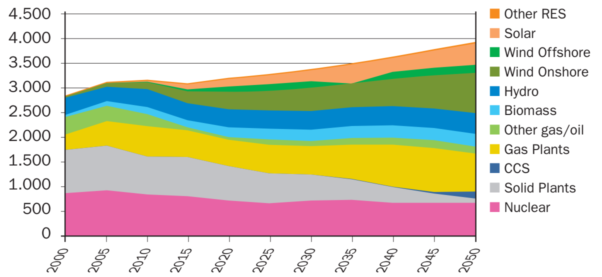


Figure 2: Electricity generation per plant type [3]

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 onshore and offshore windpower plants, 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 (i.e. by providing ancillary services), will move, to a large extent, from 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 different geographical locations.

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 [4], 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 to defer distribution networks upgrades 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 large flexibility range in both power flow directions and usually a fast reaction time.

Ubiquitous sensors will vastly increase the power system observability: with the proliferation of distributed generation, the decline of sensors and innovative solutions costs over the next few years, the inclusion of sensing and monitoring systems is starting to make compelling economic sense. This is essential for providing grid operators with a holistic view of the grid and its critical components [5] and will result in many more measurement points at all voltage levels, such as Phasor Measurement Units (PMU's), smart metering infrastructure and other power and voltage measurement systems.

Large amounts of fast reacting distributed resources could 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 [6].

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 (FCR) (possibly imposed participation through regulation) and/or Balance Restoration Reserves (BRR).

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 monitoring, operating and planning methods. Without the availability of 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 technologies. IoT can lead to a completely rethinking of LV grid operation use cases. The amount of IoT-ready devices (sensors, meters, inverters, home management systems, etc.) in LV grids is surging. These appliances can be used for additional services like forecasts of load, generation and flexibility requests.

*In short, ELECTRA foresees **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.*

The Web-of-Cells architecture

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 this reason, ELECTRA proposes a new cell-based distributed control framework named 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 over 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 tie-lines 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 supervises its operation and, if needed, is able to override it. A CSO (present DSO/TSO) can operate multiple cells (also non-adjacent), each one having its own CC. The CC includes functions and services conventionally provided by DNOs, DSOs, and TSOs or by new network operators. Roles and responsibilities are detailed and the functions required for the CC are summarized below. It is anticipated that the CC will provide autonomous control of balance/frequency and voltage. This could radically change the present paradigm, involving a central TSO control room/centre, to instead require significantly reduced manual operator interaction for real-time control.

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 is able to operate both in grid-connected and in island mode.

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 to be implemented in each cell, which are:

- Balance Restoration Control (BRC)
- Adaptive Frequency Containment Control (aFCC)
- Inertia Response Power Control (IRPC)
- Balance Steering Control (BSC)
- Primary Voltage Control (PVC)
- Post Primary Voltage Control (PPVC)

These use cases are characterized by three fundamental characteristics:

- Solving local problems at cell level,
- Responsibilization with local neighbour-to-neighbour collaboration, and
- 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. The cell power exchange set-points correspond to a system balance and if each cell adheres to its set-points, 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 active power versus frequency (dP/df) droop in response to real-time frequency and tie-line deviations from their nominal values. The output of the FCC functionality is as a multiplication coefficient used to modify the nominal Cell Power Frequency Characteristic (CPFC). The latter parameter is specified by a set-point received from a system-level process. A cell level *frequency droop parameter determination* function receives the cell's CPFC set point (cell's contribution to the system NPFC – Network Power Frequency Characteristics) for the next time step. 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 the devices, load and generation forecasts of all busses, 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 f*requency droop parameter determination* function determining the requested active power droop setting for each frequency droop device. Each of these receives its droop setting for the next time period and will continuously monitor the frequency deviation and consequently modify its active power output in accordance to its droop setting. This droop setting is continuously adapted 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 a scaling factor to achieve that most FCC activations are done in cells actually causing the deviation. This should mitigate 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.

As mentioned above, more and more grid integrated electricity generation is going to be converter based. All PV power plants as well as a high share of wind power plants already use converters as grid interfaces. Hence, the presence 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 that additional synthetic inertia is supplied (by managing suitable flexible resources), to complement the physical inertia of the system. A cell level *ROCOF (df/dt) droop slope determination function* receives a cell's moment of inertia set point (cell's contribution to the system inertia) for the next time period. A *merit order decision function* ranks the available ROCOF droop devices based on cost and location. This is done based on availability and cost information received from them, 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 *ROCOF droop slope determination* function that defines the requested ROCOF droop slope setting for each ROCOF droop device that will receive its droop setting for the next time period. It will then continuously monitor the ROCOF and modify its power output in accordance to its droop setting. No dead band will be used so that an action is taken even on the slightest ROCOF values. 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 dead band combined with a low amount of inertia provided by synchronous generators could result in high frequency fluctuation and so in the 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 activations based on local observables and losing the benefits of imbalance netting. BSC implements a distributed/decentralized coordination scheme where neighbouring cells mutually agree on changing their tie-line active power flow set points and this way reduce the amount of BRC reserves that have been activated in each cell. This can be considered as an implementation of a localized imbalance netting mechanism. Specifically, this use case will implement a corrective BSC functionality, which determines new set-points for the BRC controller, thereby causing the deactivation of resources previously activated by BRC.

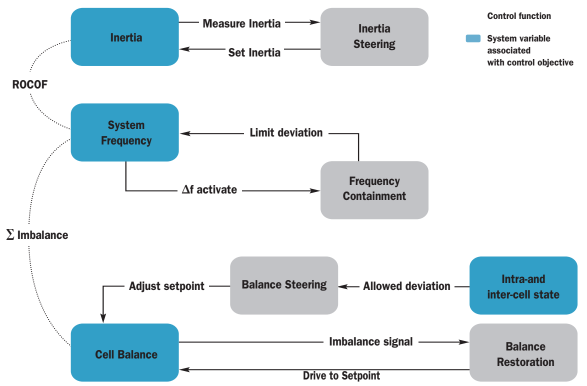


Figure 3: WoC balance control functions

Voltage control functions (see Figure 4) are 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. Even at LV and MV level it could influence a cell's balance.
Additionally, ELECTRA proposes a **Post-Primary Voltage Control (PPVC)** functionality determining set-points 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 set-point recalculation), or when one of the pilot nodes reports a voltage violation (i.e. a voltage deviation outside the limits: corrective set-point recalculation). ELECTRA assumes there is no constant requests by the PPVC function of all pilot node voltages, 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 set-point providing function* to initiate the calculation of new set-points. As input for this set-point calculation, information is collected from the (voltage) *reserves information provider* function (availability of voltage reserves), the *tie-line power flow set-point provider* function (reactive power-flow profile set-point at the cell tie-lines), 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 set-point providing* function performs an Optimal Power Flow (OPF) to calculate voltage set-point settings keeping all nodes within the limits according to valid standards and minimizing power flow losses in the cell. The *PPVC controlling* function then sends the calculated set-points to the PVC droop nodes, controllable Q nodes, capacitor banks and On-load-tap-changer-transformers (OLTCs).

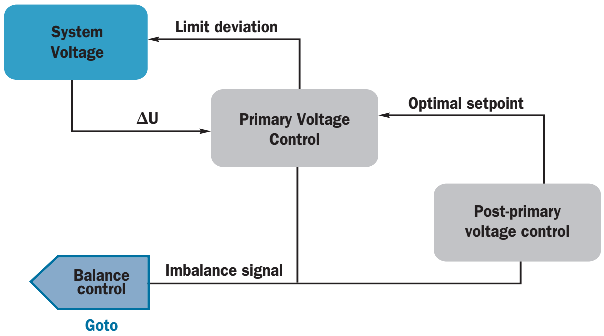


Figure 4: WoC voltage control functions

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 cell and inter-cell level. These are functions related to the observables (input for detecting if a corrective action is needed) or actuations (e.g. activating power to realize the correction): mainly at device and flexibility resource 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. Table 2 gives an overview of all use case and the related control, observer and actuator functions. More details on the related control function are presented in ELECTRA Deliverables D6.3 and simulation results in D6.4.

ELECTRA Use Case	Related WoC control (c), observer (o) and actuator (a) functions	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 Set-point Provider (a)	• Reserves Information Provider • Load & Generator Forecaster • DER - Controllable P device
Adaptive Frequency Containment Control (aFCC)	• Frequency Drop Parameter Determination (c) • Merit Order Collection (c) • Merit Decision (c) • Adaptive CPFC Determination (c) • Frequency Observation (o) • (BRC) Imbalance Determination (c)	• Cell CPFC Set-point 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 Drop Slope Determination (c) • (BRC) Imbalance Determination (c)	• Cell Inertia Set-point Provider • Reserves Information Provider • Load & Generator Forecaster • DER - ROCOF droop device
Balance Steering Control (BSC)	• Tie-line Limit Calculation (c) • Cell Set-point Adjusting (c) • Tie-line Active Power Observation (o) • Imbalance Determination (BRC) (c)	• Tie-line Active Power Flow Set-point 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 - Controllabe Q Device (a) • Capacitor banks (a) • OLTC (a)	• Reserves Information Provider • Load & Generator Forecaster • Tie-Line Power Flow Set-point Provider

Table 2: ELECTRA Web-of-Cells use cases and the related control, observer and actuator functions

Cell cooperation and interconnected operating modes

For the further analysis and evaluation of cell cooperation and interconnected 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 the 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 hardware enabled rapid prototyping, allowing 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 a more decentralized and distributed operation of power systems 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 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, effectively 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 be attributed to the non-optimized design of the fuzzy controllers used for the adaptive functionality. 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 platforms 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.

The ability of IRPC to improve ROCOF/inertia time constant 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 dead band. 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 very small, 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.
The reduction of system inertia could have negative impact on mechanical generators (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 ELECTRA 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.
Balancing and frequency 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.

Roles and responsibilities

A cell is managed by a so-called **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.
A CSO can be responsible for many cells, each one respectively controlled by a cell controller. This could lead to 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, FCC, 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; see Figure 5).

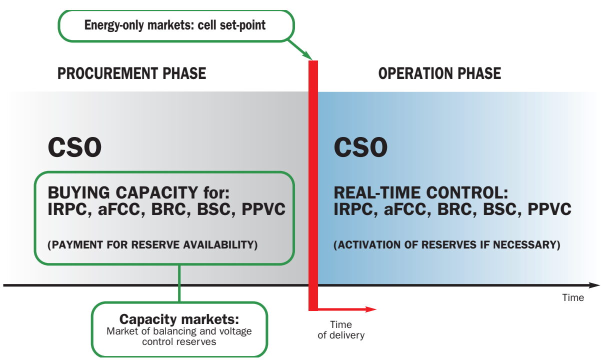


Figure 5: WoC procurement and real-time operation phase

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 BRPs and Aggregators.

After receiving energy schedules, the 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, which 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 **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, day ahead and intraday 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.

WoC market integration

Products and related market design elements

Within the WoC control architecture the market is an *exchange*, as the type of organized marketplace where the CSO and the Balance and Voltage Control Service Providers (BSPs) meet to trade balancing and voltage control products, in a voluntary, non-discriminatory and transparent way. *Uniform auction* is the proposed instrument to promote competition in the procurement of balancing and voltage control products; the CSO collects all the bids 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 offer lower or equal price to the MCP. All winners receive the same price ("pay-as-clear"), independently on their bids and offers.

New kinds of balancing and voltage control products are developed and traded in the market (see Figure 6 and Figure 7).

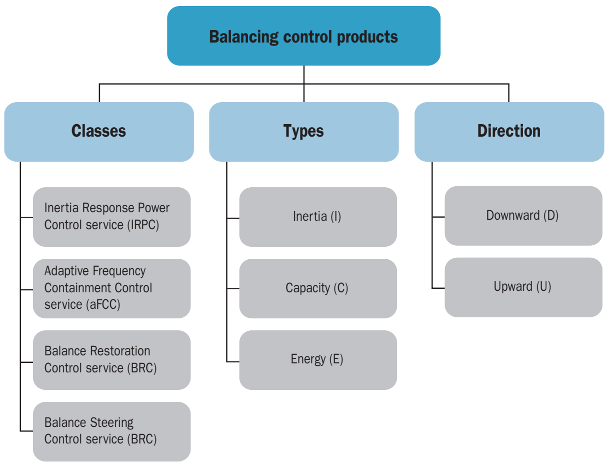


Figure 6: Categorization of balancing control products

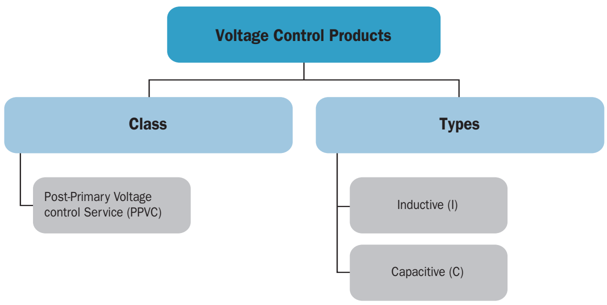


Figure 7: Categorization of voltage control products

The classes of **balancing control products** are the services for *IRPC, FCC*, *BRC* and *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 3.

Characteristic	IRPC	aFCC	BRC	BSC	PPVC
Ramping	> 1MW•s/s	> 1 MW/s	> 10 MW/min	> 10 MW/min	> 5 MVA/min
Full Activation time	< 1 s	2-5 s	2-5 s	10-30 s	>30 s
Minimum and Maximum quantity	< 1MW•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				
Mode of activation	Merit order	Merit order	Merit order	Merit order	Optimal power flow calculation

Table 3: Min. requirements for standardized control products

A set of general, balance planning, product provision and imbalance settlement **market design elements** is considered within the WoC power grid structure

General elements: within the WoC 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.

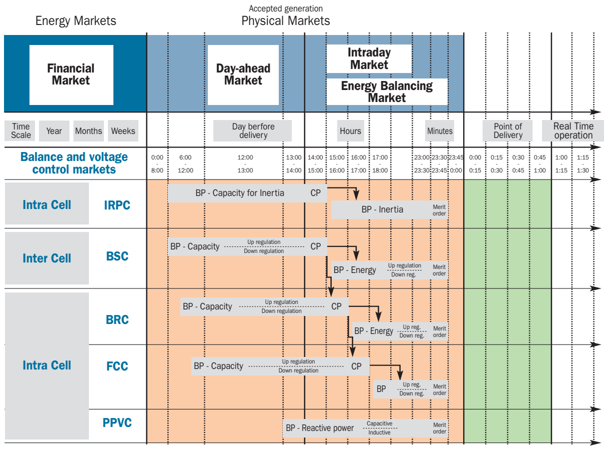
Balance planning elements: within the WoC, producers, consumers and traders of electricity have a balance obligation. Electricity produced from RES participate fully in the balancing mechanisms. This means that they have the same responsibilities as other type generators, and are allowed to provide balancing 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. The particular time should be selected to allow the BRPs to have sufficient time to prepare the initial energy schedules and the CSOs to have 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, FCC, 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 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. 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.

Market sequence organisation

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.



BP: Bidding process; CP: Clearing process

Figure 8: Timing of submarkets for balancing/voltage control

In a day-ahead market (DA), which is established at 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 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, FCC, BRC, BSC and PPVC services and the CSOs procure them. Each balancing and voltage control product is traded in a separate sub-market. 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.

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.

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 are seen in Figure 9.

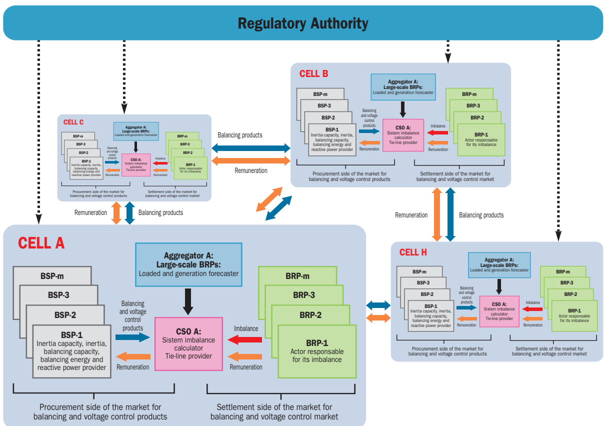


Figure 9: Interactions of the market actors for balancing and voltage control services

Outlook

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, cell level and inter-cell level. The physical, single device level 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 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. The same applies also for the IRPC: new procedures and rules are needed. 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.

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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 system

Glossary

aFCC	Adaptive Frequency Containment Control
BP	Bidding Process
BRC	Balance Restoration Control
BRP	Balancing Responsible Party
BRR	Balance Restoration Services
BSC	Balance Steering Control
BSP	Balance and Voltage Service Providers
BTU	Bid Time Unit
CC	Cell Controller
CHP	Combined Heat and Power
CP	Clearing Process
CPFC	Cell Power Frequency Characteristics
CSO	Cell System Operator
CoBA	Coordinated Balancing Area
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
FCR	Frequency Containment Reserves
FRC	Frequency Restoration Control
GCT	Gate Closure Time
GHG	Greenhouse Gas
HV	High Voltage
ICT	Information and Communication Technologies
ID	Intra Day
IoT	Internet of Things
IRP	Integrated Research Program
IRPC	Inertia Response Power Control
ISP	Imbalance Settlement Period
LV	Low Voltage
MCP	Market Clearing Price
MO	Market Operator
MV	Medium Voltage
OLTC	On-load-tap-changer-transformers
OTC	Over the Counter
PMU	Phasor Measurement Units
PPVC	Post Primary Voltage Control
PV	Photovoltaic
PVC	Primary Voltage Control
RES	Renewable Energy Sources
ROCOF	Rate-Of-Change-Of-Frequency
STU	Schedule Time Unit
TSO	Transmission System Operator
VPP	Virtual Power Plant
WoC	Web-of-Cells

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Coordinator

Ricerca Sul Sistema Energetico – (RSE)	Italy

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