THE GRID OF THE FUTURE AND THE NEED FOR A DECENTRALIZED CONTROL ARCHITECTURE: THE WEB-OF-CELLS CONCEPT

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ABSTRACT

This paper describes a decentralized control scheme for reserves activations in the future (2030+) power system. The proposed Web-of-Cells concept has been developed within the European ELECTRA Integrated Research Programme on smart grids. The concept proposes a decentralized control scheme, focusing on local inter-cell tie-line power flow deviations. The Web-of-Cells concept, the different roles and the associated control scheme are described and discussed in detail in this paper including an outlook of validating its robustness and responsiveness.

INTRODUCTION

Based on a number of undeniable trends and evolutions related to achieving the EU SET-Plan objectives [1], it can be expected that a decentralized control concept solving local problems locally, will best address the fundamental changes in the future power system [2, 3]. The ultimate scope of the European ELECTRA Integrated Research Programme (IRP) [4, 5] is related to real-time reserves activation that takes place after the market parties ended their balancing activities, and it addresses real-time deviations compared to the scheduled balance resulting from forecast errors (in load or generation) or incidents (see Figure 1).

With the growing volume of intermittent generation from Renewable Energy Resources (RES) at all voltage levels, the increasing electrical load due to the electrification of heating and transport, and the active control of flexible loads, a number of issues related to reverse power flows, local congestions and voltage problems arise that challenge the current centralised reserves activation practice. First of all, there is a detection challenge, as local load and generation deviations in Low Voltage (LV) and Medium Voltage (MV) power distribution areas may even each other out and go unnoticed for a central system operator who bases his decisions on a global variable like frequency. Secondly, there is an activation challenge, as increasingly more reserves activations will be done using devices that are located at the LV and MV networks, and it is of key importance to ensure that such activations do not cause additional problems in these local grids.

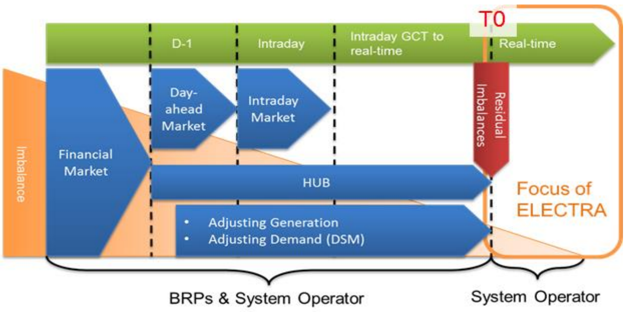

Figure 1: Timeline of Balancing Procedure

Keeping the current centralised detection and activation paradigm would require a lot of detailed local information to be collected, aggregated and communicated from all LV and MV networks to the High Voltage (HV) transmission system operator to allow the detection of local problems, and determination of a grid-secure and optimal reserves activation action using LV/MV connected flexible resources.

For these reasons, ELECTRA IRP proposes a decentralized control scheme, called Web-of-Cells concept [5]. The core focus of this approach is the handling on local inter-cell tie-line power flow deviations – comparable to the well-known Area Control Error but at cell level – rather than system frequency, where the responsibility for detecting and correcting such real-time deviations is delegated to local operators (see Figure 2). This results in less (computational) complexity and less communication. To limit the number of reserves activations in such a decentralized paradigm, a peer-to-peer inter-cell coordination mechanism is proposed to achieve a localized imbalance netting result. Obviously, local voltage problems will become more important, and must – due to their local nature – be handled by a local cell operator. This opens opportunities for a more active voltage control, where local optimal set-points are determined repeatedly based on up-to-date local information and forecasts.

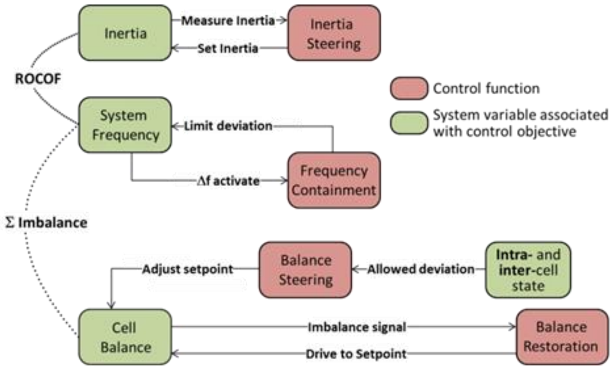

Figure 2: The Web-of-Cells control functionalities

KEY ASSUMPTIONS IMPACTING FUTURE VOLTAGE AND FREQUENCY CONTROL

ELECTRA IRP analysed control solutions are not limited to a specific scenario, but instead relate to a number of clear and indisputable trends that fit multiple future scenarios. Main aspects of these trends include:

Generation will shift from classical dispatchable units to intermittent renewables - The European Commission's Reference Scenario 2016 [1] foresees that electricity coming from RES will increase, as a share of net power generation, from around 20% in 2010 to 42% in 2030 (see Figure 3). 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.

Generation will substantially shift from central transmission system connected to decentralized distribution system connected - This will result in:

- More generation at LV and MV level increasing the risk of local voltage problems and congestions.
- 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).
- 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.

Generation will shift from a few large 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. Next to the smaller units, there will still remain large central power generators, being increasingly more of a RES nature (e.g., large onshore/offshore wind-power plants, hydro-electric power plants, marine energy parks, etc.).

- There will be more locations where incidents can happen, but each individual event having a local impact, can remain unnoticed at the global system 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.

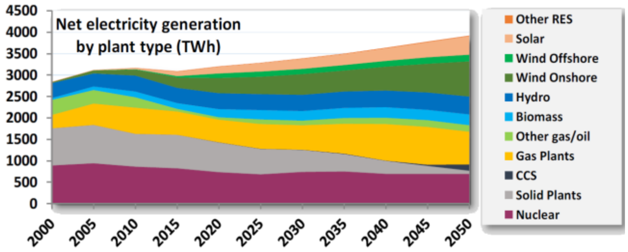

Figure 3: Electricity generation by plant type [1]

Electricity consumption will increase significantly – A gradual increase of electricity demand is expected from 21% of total final energy use in 2010 to 28% in 2050 due to electrification of heating (heat pumps) and transport (rail and electric vehicle uptake) [1]. A growth in volatile consumption, based on weather conditions and mobility needs, will increase the risk of demand peaks, voltage problems and congestions. On the other hand, heat pumps and electric vehicles represent also a large potential flexibility in the grid.

Electrical storage systems will be a cost-effective solution for offering ancillary services - Prices of electrical storage will drop and make distributed storage a competitive solution for reserve services compared to traditional resources [6]. 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 directions and usually a faster reaction time.

Ubiquitous sensors will vastly increase the power system's observability **-** Sensing and monitoring systems are essential for providing grid operators with a holistic view of the grid and its critical components [7]. This will result in many more measurement points at all voltage levels, provided by Phasor Measurement Units (PMU's), smart metering infrastructure, and other advanced power/energy measurement devices.

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) to grid operators and market parties [3].

THE ELECTRA WEB-OF-CELLS CONCEPT

The Web-of-Cells (WoC) is a cell-based architecture for decentralized balancing (frequency) and voltage control. The ELECTRA activity foresees the future power system as split into a WoC structure, where each cell is defined according to the following rules (see Figure 4):

- A group of interconnected loads, concentrated generation plants and/or distributed energy resources and storage units within well-defined grid boundaries corresponding to a physical portion of the grid and corresponding to a confined geographical area.

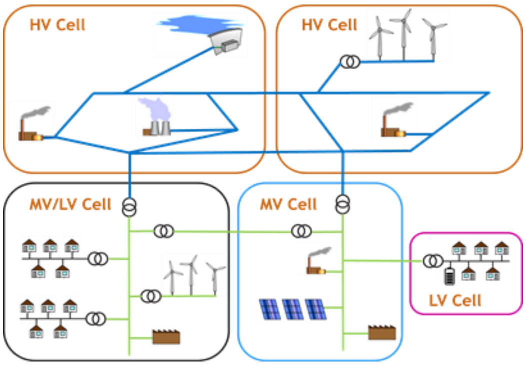

Figure 4: Schematic example of the proposed "Web-of-Cells" architecture

- A cell is by design not a microgrid. In ELECTRA, microgrids are defined as being able to operate in grid-connected as well as in "islanding" mode [7]. Being able to operate in islanding mode is not a requirement of a cell. However, as technologies mature and distributed controls become embedded in systems, the cells will more and more have attributes of microgrids leading to future integrated grids that are a combination of WoC that to a great extent, can operate in islanding mode as well as meeting the needs of the identified essential loads with available cell resources.
- A cell is in 'balance' when it is able to follow the scheduled consumption/generation schedule that was agreed between the Balancing Responsible Parties (BRP) and the Transmission System Operator (TSO) at T0 (see Figure 1).
- Cells have adequate monitoring infrastructure, as well as local reserves capacity enabling them to resolve voltage and cell balancing problems locally:
  - It is not required that cells must be able to operate in islanded mode, i.e., they can rely on structural imports or exports for their local BRP market-based balancing (microgrid capabilities are optional).
  - Only for the real-time resolution of local imbalances or local voltage regulation, it is expected that sufficient local reserve capacity is available. The procurement of reserves capacity is not considered at this stage, but it is proposed that guidelines, similar to those currently employed at Control Area level, are used to define the type and amount of reserves capacity required for each cell.
- Cells are connected to neighbouring cells via inter-cell physical tie-lines where multiple connections between cells are possible. At a given point of time, any connection can be either open or closed.
- A cell is managed by a so-called Cell System Operator (the transmission or distribution 'Cell Operator') with the following attributes:
  - Multiple BRPs/aggregators can be active in a cell.
  - Extended roles, responsibilities and corresponding functions – as for example identified by the European projects Grid4EU and evolvDSO [8, 9] – are being used for handling local problems.

Using the above WoC definition the following specific characteristics can be observed:

- Local problems are usually solved within a cell where local observables are used to decide on local corrective actions to handle local issues (i.e., localization and local empowerment);
- Communication complexity and latencies as well as computational complexity are minimized (i.e., divide and conquer);
- Local grid conditions are explicitly taken into consideration when deciding what kind of resources are used;
- Provision of a distributed bottom-up approach for the restoring of the system balance;
- Focus more on balance restoration – and thereby restoring frequency as well - rather than the current traditional sequence of Frequency Containment followed by Frequency Restoration.

ROLES IN THE WEB-OF-CELLS

Today roles and responsibilities in the power system are implemented in very different ways across Europe. Analysing the responsibilities of the different market participants some key roles can be identified for the future energy market design within ELECTRA's WoC approach.

As a physical entity, a *Cell System Operator (CSO)* can be responsible for many cells 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.
- Containing and stabilizing local voltage within safe boundaries.
- Operating in real-time the state of a cell and the whole power system has to be monitored to ensure continuous secure operation and the appropriate response to disturbances. A CSO has the role of monitoring the system and its interconnections, 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.
- Several possibilities for the role of the CSO in the future market structure can be taken into account: similar to the behaviour of DSOs nowadays (so the CSO would facilitate the market resolution but without direct participation), while other options include the active involvement of the CSO as retailer or its operation as a single entity (producer or prosumer) to individually bid in the market.

Producers are the owners of the generation units, responsible for their operation. The producers feed in electricity in the cell and they receive the price formed in pool.

Consumers/end-users are the customers connected to the cell which pay a price for the energy use. This price has been previously agreed, usually, with a retailer.

Prosumers can act as both consumers and/or producers. They can generate a certain amount of energy for self-supply, exporting the difference to the cell. They can, alternatively, take advantage of the market prices to sell the whole energy they produce and buy the required electricity at a lower price. 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.

The *aggregators* are the entities, that gather the flexibility by forming Virtual Power Plants (VPPs), and enable the participation of those smaller units in the AS markets. Other times, these small resources can enter into the market as part of the portfolio of a retail supplier or an Energy Service COmpany (ESCO)

The *market operator* 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 *retailer* is the final entity that will establish the contracts directly with the end-users. Its main responsibility is to provide the electricity and, in general, the energy services to its customers.

THE WOC CONTROL SCHEMES

The WoC control scheme is characterised by the interaction of six high-level functionalities and characterized by three fundamental characteristics:

- Solve local problems locally;
- Responsibilization with local neighbour-to-neighbour collaboration;
- Ensuring that only local reserves providing resources will be used whose activation does not cause local grid problems.

Cells are treated as ‘physical clusters’ that are responsible for making their actual net active power import/export profile match their forecasted profile (which relates to system balance). This is the responsibility of the *Balance Restoration Control (BRC)* functionality, which maintains and restores the system balance in a bottom-up manner. This is done based on local observables (tie-line power-flow deviations) and resembles the current Frequency Restoration Control (FRC), except that BRC is not a slower (secondary) control, but instead is a fast primary control – using many local fast ramping resources like flexible loads or storage – that runs at the same time as the FCC control (instead of taking over from FCC). Deviations that are 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.

An *Adaptive Frequency Containment Control (FCC)* functionality is proposed. Each cell is assigned a portion of frequency droop responsibility (Cell Power Frequency Characteristic), but actual reserves (droop) activations are dynamically scaled so that reserves activations are prioritized in cells that are causing deviations, and are minimized in cells that are not causing activations. 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 scaling factor is determined based on a combined observable of frequency deviation and cell balance error. This scaling behaviour is highly configurable and can take the form of a basic 0/1 factor to a value provided by a fuzzy logic controller. FCC is running at the same timescale as BRC, so both join forces in containing frequency deviations.

Since the contribution of synchronous generators providing inertia through their rotating mass is expected to decline, and vary dramatically given the instantaneous energy mix, ELECTRA IRP introduced an *Inertia Response Power Control (IRPC)* functionality, which ensures that a constant inertia is provided by supplying additional synthetic inertia to complement the physical inertia.

To complete the Balance/Frequency Control related functionality, there is also a *Balance Steering Control (BSC)* functionality. This one compensates for the loss of imbalance netting benefits in the bottom-up balance restoration based on local observables. As each cell is maintaining and restoring its own local balance, more reserves would have to be activated than in the current centralistic control scheme. BSC mitigates this amount of excess reserves activations by changing cell balance set-points in a neighbour-to-neighbour coordinated manner, this way implementing what could be called a distributed imbalance netting solution. Actually two variants are proposed and evaluated: a corrective one, in which activated reserves are deactivated by balance set-point adjustments, and a proactive one, where reserves activations by BRC are pre-empted by the balance set-point adjustments.

Voltage control functions (see Figure 5) are active at all voltage levels in a very dynamic manner: not only to correct voltage deviations that violate regulatory safe-bands, but to minimize power-flow losses too. *Primary Voltage Control functionality (PVC)* will be present at all voltage levels, and at LV and MV levels it could influence a cell’s balance. Next to this, there is a *Post-Primary Voltage Control (PPVC)* functionality determining set-points for

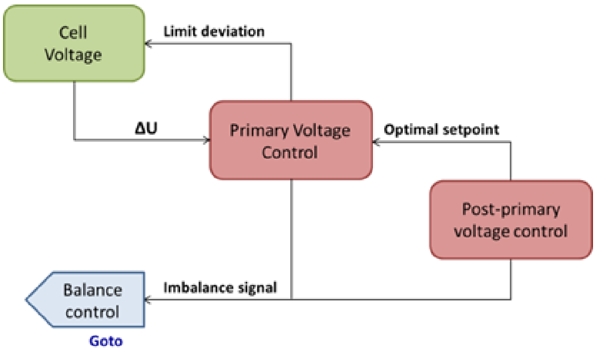

Figure 5: Voltage Control Scheme functionalities

all resources that can contribute to voltage control (and power flow loss minimization): like PVC (AVR)-resources, Q-controllable resources, tap-changing transformers, capacitor banks, etc. PPVC calculates safe and robust voltage control set-points for all these resources taking into account the forecasted local grid status and minimizing power-flow losses. It also ensures that its set-points do not affect neighbouring cells (on the other side of the tie-line/transformer). New set-points are calculated periodically (based on new forecast updates) or whenever a voltage violation is reported by one of the pilot nodes.

KPI-BASED PROOF-OF-CONCEPT VALIDATION METHODOLOGY

The validation and testing of future frequency and voltage control algorithms – as introduced above – is an essential effort towards the integration of novel control developments into future power systems.

In order to systematically evaluate the WoC control schemes in ELECTRA IRP, system modelling and simulation tools as well as realistic, near real-world laboratory conditions are used to prove the system performance. In order to plan, design, implement and compare simulation results and lab experiments from different ELECTRA IRP partners, a Key Performance Indicator (KPI)-based validation methodology is proposed [10]. The goal is to define KPIs (addressing WoC integration and technical issues – an example is provided in Table 1) which can be implemented and measured in corresponding simulation and lab-based testing scenarios. As a result, various WoC-related validation KPIs are available which are being compared with the corresponding KPIs of a business as usual case (i.e., state-of-the-art centralized control schemes).

Table 1: KPIs for FCC+BRC+BSC integration validation

WoC Integration KPIs	Technical KPIs
Remote boundary flow changes	Time to frequency restoration
No. of cells participating in an event	MVA*km used for reserve delivery
No. of local reserve activations	Frequency nadir
	ROCOF magnitude

Moreover, this kind of validation procedure also allows the identification of relevant KPIs that can be implemented and analyzed by individual laboratories for the ELECTRA IRP proof of concept. An important further aspect of this approach is that it supports the selection of the most suitable laboratory infrastructure available within the consortium.

CONCLUSIONS

The wholesale deployment of renewable energy sources and distributed generation connected to the network at all voltage levels is calling for radically new approaches for real-time voltage and frequency control that can accommodate the coordinated operation of millions of devices, of various technologies and many different scales, dispersed across the power system. The WoC concept is flexible enough to cope with the operational problems that are expected to arise in this evolving context. Simulation activity of the WoC concept on selected model networks as well as the definition of the testing methodology are almost completed, and the remaining period of the ELECTRA IRP activity will be fully dedicated to the WoC experimental validations at laboratory level.

Acknowledgments

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