VALIDATING THE ELECTRA WEB-OF-CELL CONTROL CONCEPT – AN OVERVIEW OF POSSIBLE SIMULATION ENVIRONMENT ENHANCEMENTS

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ABSTRACT

It is expected that future power systems will be characterized by a high share of renewables. Nowadays, a shift from conventional dispatchable bulk generators to intermittent converter-coupled generation units can be observed. This trend, that will be always more significant in future, will affect the operation of the underlying power systems. Advanced automation and control concepts have the potential to address these challenges by providing new intelligent solutions and products. A proper validation of these new technologies is needed before their field installation. However, suitable development and testing approaches and the corresponding tools able to address system-level issues are partly missing until now. The aim of this paper is to discuss some experiences which have been made with simulation-based approaches in the EU-funded ELECTARA IRP project during the development and testing of a sophisticated distributed real-time control concept and its corresponding functions.

INTRODUCTION

The ongoing replacement of conventional bulk generation with new power plants with different characteristics is one important change that is taking place in today's power systems making its operation more complex. This trend, driven by political, environmental, and economic reasons is expected to be still growing in the next years. Conventional big power plants are nowadays replaced by smaller generation units, in most cases by Renewable Energies Sources (RES) [1]. They are connected at any voltage level and distributed along the electricity network. The characteristic of such Distributed Generators (DG) raises the concern of coordinating these new resources in supporting the power system operation.

Due to non-continuous power production, difficultness in forecasting, and not fully dispatchability of such resources several problems arise. In order to master the higher complexity and the stochastic behaviour of these grid components, advanced automation and control solutions and corresponding sophisticated algorithms are being realized resulting in a smarter grid behaviour [2]-[4].

Such approaches and technologies have been or being currently realized and validated in several research and development projects worldwide. Cell-based control concepts – as it has been previously developed within the ELECTRA IRP project [5] or other activities [7] – are highly interesting approaches in order to address the aforementioned challenges.

However, the proof-of-concept evaluation of such sophisticated smart grid solutions, especially the advanced control and automation concepts, is still a challenge through the whole development process (i.e., form the conceptual phase to the roll-out and field installation). Up to now suitable validation and testing methods at system-level covering power system and automation/ICT[1] issues are partly missing [8].

Simulation-based validation approaches have a big potential and can cover several stages of the development process but they need to be improved and extended. This work reports on some experiences which have been made during the control concept development and validation in the ELECTEA IRP project.

WEB-OF-CELLS APPROACH

In order to address the above outlined challenges and needs, the EU-funded ELECTRA IRP project has developed the so-called Web-of-Cells (WoC) real-time control framework for operating the future power systems with a high share of renewable sources and controllable loads [3]. In the following the overall concept and the corresponding control schemes are briefly outlined and validation and testing needs for the proof-of-concept evaluation are discussed.

Cell-based Real-time Control Concept

The WoC concept considers that the power system is divided into smaller subsystems (i.e., cells) and reorganized in new cell-related roles and responsibilities as sketched in Figure 1. Each cell has to contribute to balance/frequency and voltage controls and it is responsible for its behaviour at its boundaries. Cells can be considered as a group of interconnected conventional and distributed generators, storage units and controllable loads within well-defined electrical and geographical boundaries. They usually have enough flexibility to solve local problems – deviations from the scheduled consumption/generation schedule – locally within a cell.

The approach looks quite similar to the well-known microgrid approach but the main difference is that cells are not self-sufficient and they are not intended to operate in islanded mode. However, the WoC concept is designed in such a way that also grid-connected microgrids can be included.

[1] Information and Communication Technology

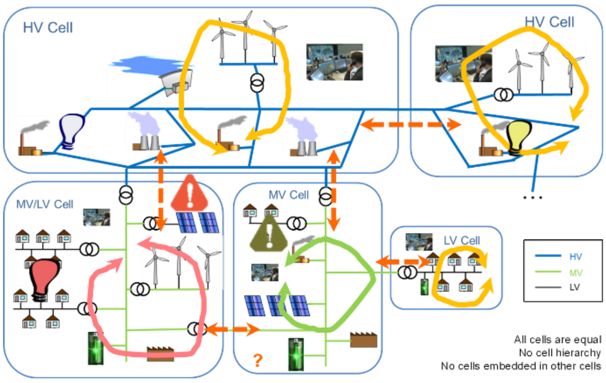

Figure 1: Schematic overview of the WoC architecture [3]

Control Schemes

Within the WoC it is foreseen that the so-called cell system operator has a clear knowledge of what is happening within its control boundaries. It is therefore expected that in the future power system ICT/automation, a key enabling factor, will permit a high grid observability and controllability of resources (distributed generators, controllable loads, tag-changing transformers, etc).
The WoC control scheme is characterised by the interaction of six high-level functionalities and characterized by three fundamental characteristics [3], [9], [10]:

- Solve local occurring problems within the cell,
- Enable responsibilization through local neighbour-to-neighbour collaboration, and
- Ensuring that reserve activations of local resources (i.e., generators and loads) do not cause any grid problem.

ELECTRA cells can be seen as a kind of physical clusters or Virtual Power Plants (VPP) that are responsible for making their actual net active power import/export profile according to their scheduled profile. In order to realize such a behaviour, a set of different balancing and voltage control schemes has been developed as outlined in Table 1 and Table 2. This table shows also the difference to the currently used concepts.

Table 1: Overview of ELECTRA balancing control schemes

	Current Grid	Future 2030+ Grid
Balance Control	---	Inertia Steering Control
	Frequency Containment Control (FCC)	Frequency Containment Control (FCC)
	Frequency Restoration Control (aFRC)	Balance Restoration Control (BRC)
	Frequency Replacement Control (mFRC)	Balance Steering Control (BSC)

Table 2: Overview of ELECTRA voltage control schemes

	Current Grid	Future 2030+ Grid
Voltage Control	Primary Voltage Control (PVC)	Primary Voltage Control (PVC)
	Secondary Voltage Control (SVC)	Post-Primary Voltage Control (PPVC)
	Tertiary Voltage Control (TVC)	

WOC DEVELOPMENT AND TESTING

In order to show how the WoC approach is working a prototypical realization and a proof-of-concept has been carried out. In the following the main development and validation steps are outlined.

Concept and Function Development

The whole concept and the corresponding control functions proposed by ELECTRA have been specified and developed using the Smart Grid Architecture Model (SGAM) and IEC 62559 use case methodology [9], [10]. After having specified the different control schemes and the corresponding functions through the aforementioned tools, they have been implemented in domain-specific simulation tools for a first proof-of-concept. Mainly, MATLAB/Simulink has been used at this development step to show how the individual control and observable functions are working.

Proof-of-Concept Validation

Since the ELECTRA project is mainly a pure research project no field installations and corresponding demonstrations/tests where foreseen. The main possibilities for validating and testing the WoC control approach and its corresponding functions where the use of simulation tools and for more realistic set-ups also the usage of power system/smart grid laboratories provided by the consortium partners. Therefore, the validation goals for analysing the WoC approach can be summarized as follows [11]:

- Experimentally implement WoC-based distributed real-time control in a number of respected European laboratories,
- Proof that local problems can be solved locally within a cell,
- Demonstrate the effectiveness of distributed controls in relation to a number of selected grid scenarios taking laboratory evaluation capabilities of ELECTRA partners into account,
- Investigate the local coordination of numbers of devices when subject to uncertainty in system operation while maximizing the effective utilization of flexibility,
- Compare performance demonstrated across multiple laboratories and with traditional approaches (i.e., business as usual case), and
- Understand on the basis of experiments, the implications of potential controller conflict(s) and the relative merits of different controls.

Having these goals in mind, overall 15 different testing scenarios and corresponding experiments have been identified during the validation phase. This selection reflected the laboratory and personnel capabilities of the ELECTRA partners. At the end the most important combinations of the balancing and voltage control functions have been prototypically realized and tested (i.e., IRPC and FCC; FCC and BRC; FCC, BRC and BSC) as well as voltage control (i.e., PVC and PPVC).

Lessons Learned

As mentioned above the individual control functions have been mainly implemented in MATLAB/Simulink. Taking the research nature of ELECTRA into account only a proof-of-concept evaluation of selected scenarios was necessary (i.e., up to Technology Readiness Level TRL4). Therefore, there was no need to fully implement the whole WoC control concept in corresponding embedded controllers. Moreover, it turned also out that the fastest way to proof the concept was to realize co-simulations and hardware-in-the-loop experiments in the individual laboratories of the partners [12]. However, usually, simulation tools are not really designed in such a way that they can be easily coupled together or together with laboratory equipment. In the following some approaches are being discussed which addresses this topic.

SIMULATION ENHANCEMENTS

In ELECTRA possibilities how to couple different, most suitable simulation approaches and tools (i.e., covering the power system, ICT environment, control concept) have been investigated for proofing the WoC concept. The focus of the work was on the co-simulation of power systems with connected power and ICT components available in the partners' laboratory environments (covered by real-time controller and power hardware-in-the-loop simulations).

Suitable Simulator Couplings

One of the main reasons to run such co-simulation experiments is to exploit the main features of the different software tools in order to simulate/emulate complex cyber-physical system behaviours, like the aforementioned WoC concept.
During the ELECTRA development and validation activities different tools have been used. The following list provides an overview of tool couplings which are considered as the most promising once:

- *DIgSILENT PowerFactory and MATLAB/Simulink:* In this case the power of PowerFactory in modelling and simulation of large electrical grids and the easy to use features of Simulink in terms of modelling control systems can be exploited.
- *DIgSILENT PowerFactory and OPAL-RT:* Since the host PC of an OPAL-RT real-time simulation system has an instance of Simulink running which is communicating with the real-time target, a connection with PowerFactory in a co-simulation set-up can be beneficial for evaluating different smart grid con-figurations covering power system and ICT/control issues. This approach is also quite helpful for connecting real power and/or controller components available in laboratories with simulators in a hardware-in-the-loop manner.
- *DIgSILENT PowerFactory and Python:* It can be very useful to have Python scripts (e.g., implementing complex computational tasks) running together with PowerFactory simulations (e.g., RMS simulation).

Realizing the last option is straight forward since PowerFactory nowadays also provides a Python interface. Scripts in this configuration can also be used to automate complex simulation scenarios in PowerFactory. The implementation of the first two options usually require some attention. In the following two approaches are being discussed. It has to be noted that PowerFactory has a built-in interface to MATLAB/Simulink but comes with some limitations.

Point-to-Point Coupling Approach

One straight forward way of realizing co-simulations is the point-to-point coupling of two tools. This work mainly investigates to run co-simulations between PowerFactory and OPAL-RT through a MATLAB/Simulink instance that is running on the host PC using TCP/IP communication as shown in Figure 2.

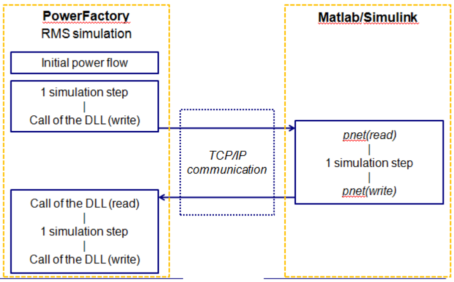

Figure 2: Point-to-point coupling approach

In this configuration the co-simulation is carried out according to the following main steps:

- Every simulation time step PowerFactory communicates through a specific library (DLL) data in a client/server fashion using socket communication (i.e., transport protocol TCP/IP).
- Between the write and read functions call Simulink is performing usually one simulation step (but can be more than one if properly managed). On the Simulink side the same communication approach is used.
- For synchronizing the two simulation environments "blocking" TCP/IP reading functions are being used.

In this case the simulations are coordinated if the step time is the same for the two simulators. If this is not the case the actual simulation time needs to be taken into account at least by one simulation tool to coordinate the process. If one considers running PowerFactory synchronized with the system clock, it also possible to run a co-simulation with OPAL-RT real-time simulator, but in this case care shall be due (by proper configuration of the overall co-simulation setup) to the overrun of the PowerFactory simulation.
In the ELECTRA context this coupling concept was used to evaluate some of the above-mentioned control schemes. Therefore, ELECTRA cells have been implemented in PowerFactory and the corresponding control functions either in MATLAB/Simulink or in Python scripts. Also, the real-time execution of the control functions by using OPAL-RT have been proven as a preliminary step before connecting real hardware components.

Framework-based Coupling Concept

If more than two tools need to be coupled and synchronized together (due to more complex validation and testing scenarios), the point-to-point coupling approach as outlined above is limited. In such a case a more sophisticated coupling infrastructure is required.

In order to tackle this issue AIT has started to realize a flexible coupling environment – called LabLink – allowing to connect different power system and ICT/automation software and hardware components.

In context of the ELECTRA validation work this kind of communication-middleware based coupling concept was used to integrate PowerFactory grid simulations together with real-time emulated converter hardware and real controller hardware (see Figure 3) [13]. In addition, dashboard-based visualisation clients and a real-time database for monitoring was connected as well.

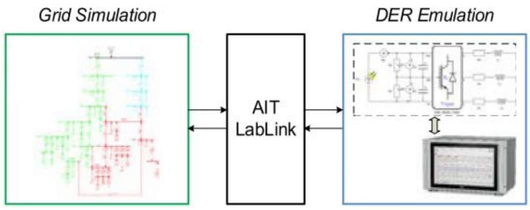

Figure 3: Framework-based coupling concept [13]

CONCLUSIONS

In order to address the requirements of future power system scenarios with a high share of renewable generation, ELECTRA IRP has introduced the WoC real-time control concept. The development and validation of the corresponding control functions has been realized prototypically. Co-simulation proved to be an effective way during the testing work by providing the possibility to overcome the limitations of a single simulation software. Mainly, two coupling approaches have been introduced and discussed. The point-to-point approach provides a straight forward way for smaller-scale co-simulation configurations whereas the framework-based approach is intended for coupling more than two tools in a more complex configuration.

Further work is needed in order to couple in broader way power system and ICT/control simulation tools or possibly even real automation devices. One possible future research and development path could be the coupling of a power system simulators like PowerFactory with a real ICT infrastructure, for example with Programmable Logic Controllers (PLC) or Remote Terminal Units (RTU)-based control systems. In this way the behaviour of the control systems and moreover their interactions with the electric energy infrastructure can be analysed in a safe way independently of using the real power units. Potential conceptional and/or implementations errors can be identified quite early in the development process without the risk of destroying real equipment. Moreover, this could also open the path for cyber-security analysis and cyber-attack effect evaluation on real ICT devices. The effect on the power system could be assessed in simulations, but the cyber-attack would be on the real ICT network.

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