ELECTRA IRP

Test Case & Test Specification / Proof-of-Concept Reporting PVC+PPVC

Performed Proof-of-Concept Tests at AIT

Table of Content

Test Case 3

<table>
<tr><td colspan="2">Name of the test case</td><td>Power quality and voltage control (PVC+PPVC)</td></tr>
<tr><td colspan="2">Narrative
“a storyline summarizing motivation, scope and purpose of the test case.”</td><td>Can PPVC replace the present secondary (local) and tertiary voltage control (global) schemes existing in power grids by a decentralized control located at a cell level? How would PPVC interact with PVC and balancing control? How would PPVC respond to different network conditions?</td></tr>
<tr><td colspan="2">System under Test (SuT):
(power system & ICT boundaries): SRPS + CTL</td><td>Power distribution network (several voltage levels), On-Load-Tap Changing Transformers (OLTC), inverter-based Distributed Energy Resources (DER) (PV, wind turbine, energy storage systems), synchronous and induction machines, (controllable) loads</td></tr>
<tr><td></td><td>Objects under Investigation (OuI)
"the component(s) (1..n) that are to be characterized or validated”</td><td>PVC+PPVC controlling</td></tr>
<tr><td></td><td>Domain under Investigation (DuI):
“Identifies the relevant domains or sub-domains of test parameters and connectivity.”</td><td>• Power system
• Control/ICT</td></tr>
<tr><td colspan="3"></td></tr>
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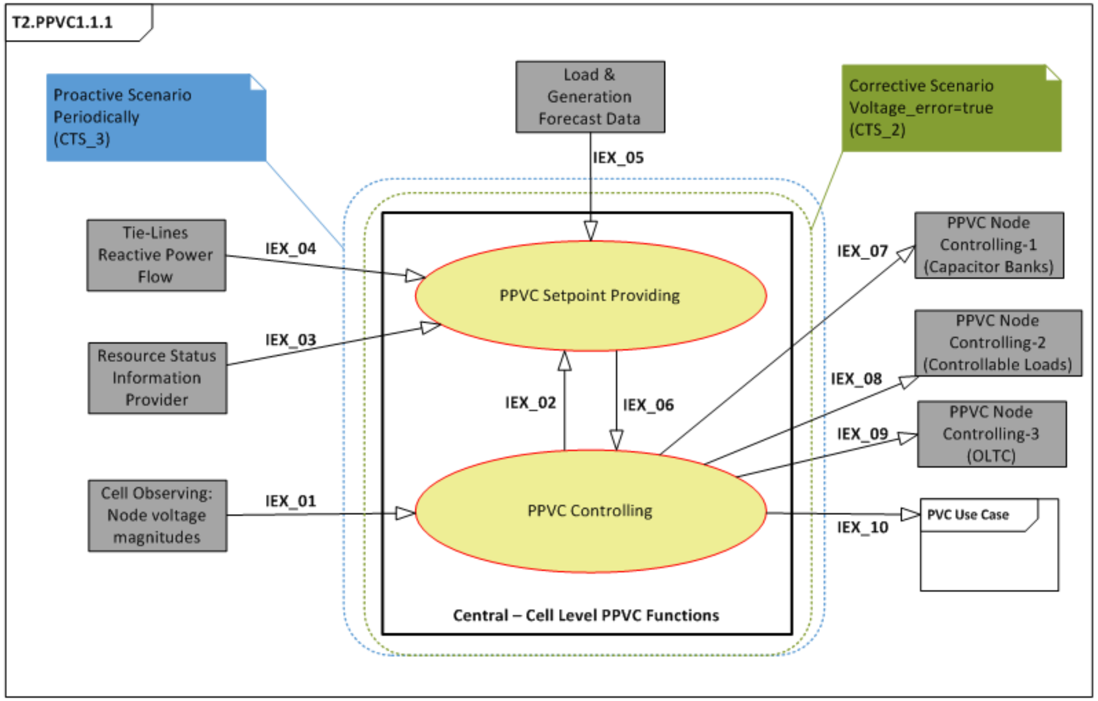
<table>
<tr>
<td colspan="2">Functions under Test (FuT)
List all functions required in operation of test system</td>
<td>


Figure 0 Overview PPVC functions

In-focus Functions: PPVC controlling, PPVC Set-point providing
Emulated functions: Reserves information provider, load and generator forecastor, tie-line powerflow setpoint provider
Observer/Actuation Function: DER-AVR device, DER-Controllable Q device
Actuation Function: Capacitor banks, OLTC
Observer function: Voltage pilot nodes
</td>
</tr>
<tr>
<td></td>
<td>Function(s) under Investigation (FuI)
“the referenced specification of a function realized (operationalized) by the object under investigation”</td>
<td>

PPVC Set-point providing
PPVC Controlling

</td>
</tr>
</table>

Purpose of Investigation *(PoI)* “a formulation of the relevant interpretations of the test purpose (e.g. in terms of Characterization, Verification, or Validation)”		3.4 Simulation-based proof-of-concept analysis of the PVC+PPVC use case, incl. sensitivity analysis, clustering concept for the identification of potential ELECTRA cells, scalability analysis, comparison with a business as usual case. 3.5 Hardware-in-the-Loop based proof-of-concept analysis of the PVC+PPVC use case incl. a selected number of DER units (PV system, Energy Storage Systems, etc.), sensitivity analysis.
Test criteria: “the measures of satisfaction that a need to be evaluated for a given test to be considered successful.” A formalization of the purpose of investigation wrt. SuT and FuT attributes.		● Optimal cell division for voltage control ● TCR28: Minimum power losses in the cell ● TCR30: Safe and robust voltage for all nodes
	target metrics (criteria) A numbered list of measures to (quantify) each identified criterion	● Minimum power losses in the cell, Reactive power flows in the tie-lines within safety limits ● Safe and robust voltage for all nodes
	variability attributes (test factors):	● Topology change resulting in change in number of tie-lines ● Loss of a line ● Loss of a generator
	quality attributes (thresholds):	● Power quality standard EN50160 ● All node voltages within the specified limit (+ or -10%)

Test Specification 3.4

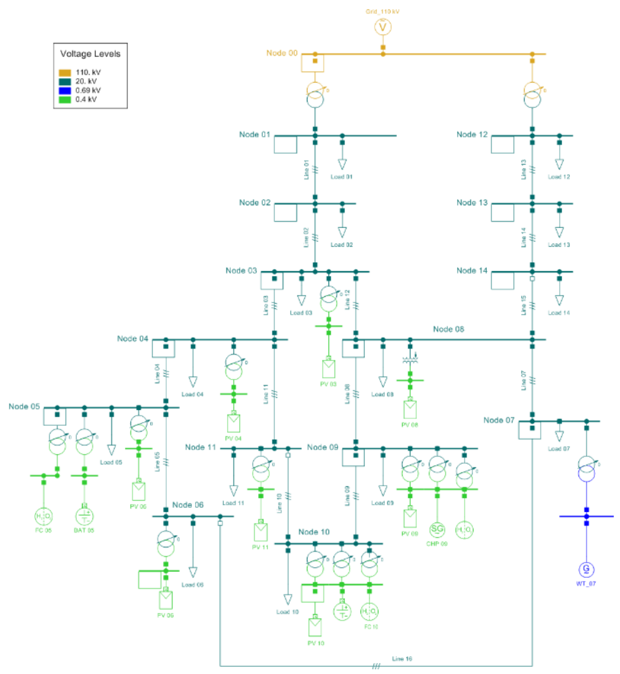
ID / Title	Simulation-based proof-of-concept analysis of the PVC+PPVC use case, incl. sensitivity analysis, clustering concept for the identification of potential ELECTRA cells, scalability analysis, comparison with a business as usual case
Ref. Test case	Test Case 3
Responsible Entity	AIT
Experiment Type	Clustering, simulation
Test System (also graphical)	Usage of CIGRE MV distribution network (original and modified version) as depicted in the following figure.  **Figure 1** The modified CIGRE medium voltage network

Table 1 Modifications to the CIGRE MV test network

	Node 3	Node 4	Node 5	Node6	Node 7	Node 8	Node 9	Node 10	Node 11
Source Type	PV;	PV	PV; FC; BAT	PV	WT	PV	PV; FC; CHP	PV; FC BAT;	PV
Source rating [kVA]	22;	22;	33; 1000 ; 1000	30;	1500	33;	30; 500 ; 500	40; 14 ; 210	10;
Tfmr rating [kVA]	500	500	500; 800; 500	800	2500	500	500; 500; 500	500; 500; 500	500

Table 2 Modifications to line length

Line lengths	Line 01	Line 02	Line 03	Line 04	Line 05	Line 07	Line 08	Line 09	Line 10	Line 11	Line 12	Line 13	Line 14	Line 15	Line 16

Research Infrastructure	---
Input parameters	• Generation profiles • Load profiles • Grid topology • Tie-line exchanges • DER controllers parameters
Output parameters	• Power losses • Node voltages
Target measures	• Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes
Test Design	Comparison of different cell-configurations and different OPF implementations
Initial system state	*Description of conditions that are prerequisites to actually run the test and initial choices of parameters.*
Evolution of system state and test signals	*Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds); incl. variability attributes*

Other parameters	*Information of data that should be tracked apart from the input and output parameters and system state, test signals*
Storage of data	*In which format are the parameters stored?*
Temporal resolution	*Discrete or continuous simulation and (if applicable) resolution of the discrete time steps*
Source of uncertainty	*In order to evaluate the quality of the test, the possible sources of uncertainties are given in how they can be quantified.*
Suspension criteria / Stopping criteria	*Under which conditions are the test results not valid or the test is interrupted*

Experiment Specification 3.4.1

Title	Simulation of PVC+PPVC with CIGRE MV test grid
Ref. Test Spec.	Test Case 3, Test Specification 3.4
Research Infrastructure	PowerFactory, Python API, Python Scripts
Experiment Realisation	Simulation
Experiment Setup (concrete lab equipment)	**A) Sensitivity Analysis of the CIGRE MV test network**
Experimental Design and Justification	**1. Calculation of normalized electrical distance** a. Calculate the Jacobian matrix and use it to obtain the *∂Q/∂u* matrix. $\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial u} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial u} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta u \end{bmatrix}, \qquad J_4 = \frac{\partial Q}{\partial u}$ b. Calculate the sensitivity matrix *B* by calculating the inverse of *J4*. $B = J_4^{-1} = \frac{\partial u}{\partial Q} \text{ where } b_{ij} = \frac{\partial u_i}{\partial Q_j}$ c. Calculate the attenuation matrix α by dividing the non-diagonal elements by the diagonal elements using the following equation. $\alpha_{ij} = b_{ij} / b_{jj}$ d. Calculate the electrical and obtain the normalized distance matrix $D_{ij} = -\log(\alpha_{ij} \,.\, \alpha_{ji})$ $D_{ij}^{norm} = D_{ij}/\max(D_i)$

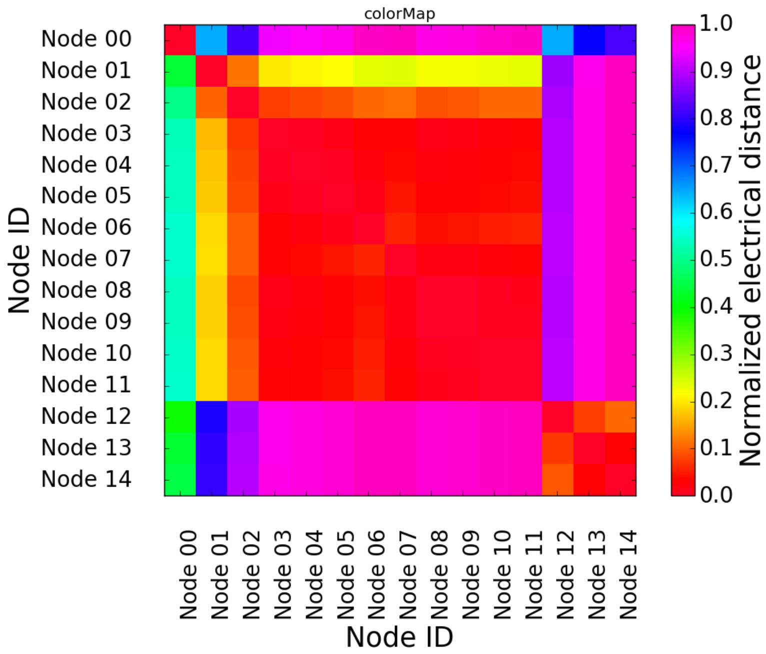
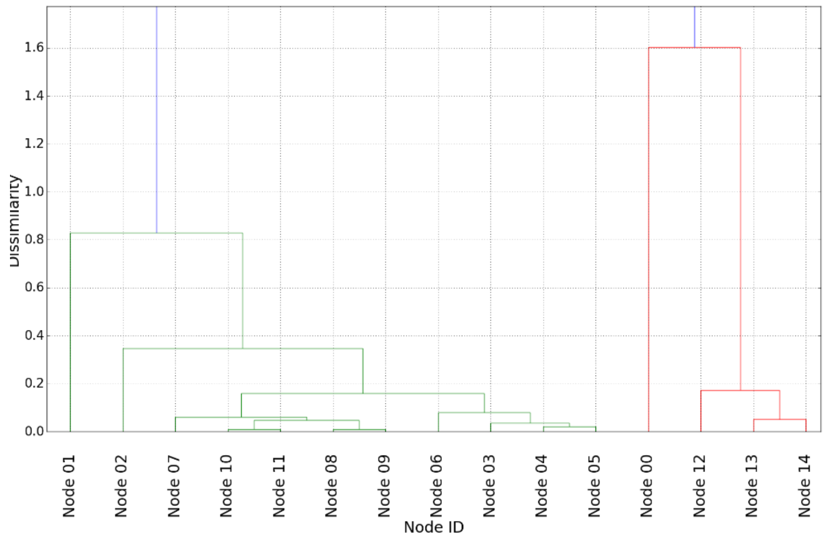


Figure 2 Color plot of the normalized electrical distance matrix for the Cigre European MV test network

The normalized electrical distance matrix presented in Figure 2 shows that the CIGRE MV test feeder has strong voltage coupling. This is essentially because the line lengths at the start of the feeder are much longer than the line lengths at the end of the feeder. This means that the nodes most susceptible to over voltage have tight voltage coupling and dividing the feeder into cells might not be possible. Ensuring cells have weak voltage coupling is important as it would limit the impact of one cell's regulations on its neighbours. One way to emphasis the utility of a cell based approach is to modify the line lengths such that voltage zones with weak voltage interdependence are created. In this work, three-line lengths have been modified (Table 2) to create regions with weak voltage interdependence. Simulations have been carried out on the network with original and the modified line lengths.

The results have been obtained by coupling two software; namely DIgSILENT PowerFactory and Python. The CIGRE network has been implemented in PowerFactory and script to calculate the normalized electrical distance has been implemented in Python. SciPy library in Python has been used to obtain the results for hierarchical clustering.

	B) Hierarchical clustering Hierarchical clustering is one method of defining clusters from a data set. It requires distance matrix and linage criterion as input and generates a hierarchy of clusters. A user can then decide upon the best number of clusters based in additional and/or prior information. One method for choosing the best number of clusters is plotting a dendrogram and a scree plot. In literature the knee point in the scree plot is commonly used as the reference point for the best number of clusters. Dendrograms presented in figure 3 and 6 show the impact of line modifications. In Figure 3 (original line lengths) there is tight voltage coupling, while in Figure 6 three cells are clearly visible.  **Figure 3** Dendrogram for clusters produced using ward linkage based agglomerative hierarchical clustering

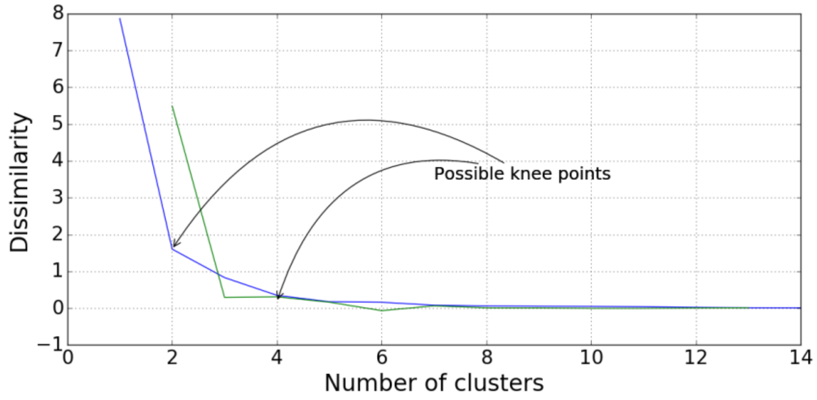


Figure 4 Scree plot for the dendrogram

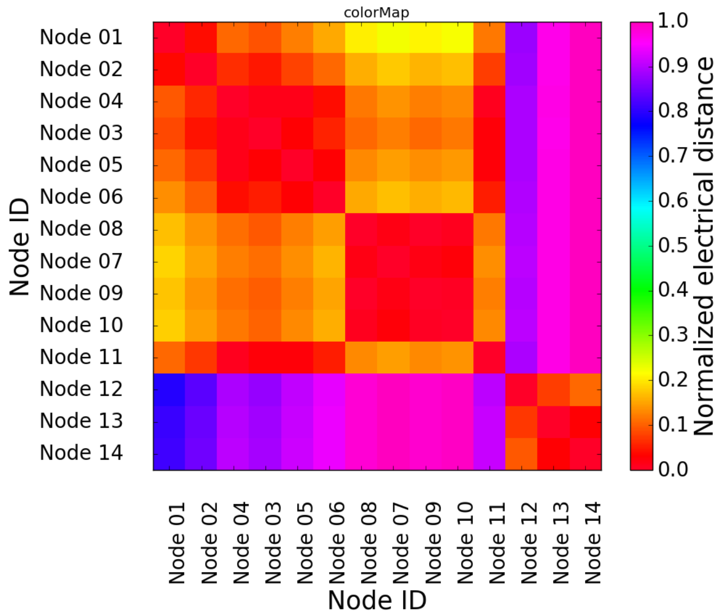


Figure 5 Color plot of the normalized electrical distance matrix for modified line lengths

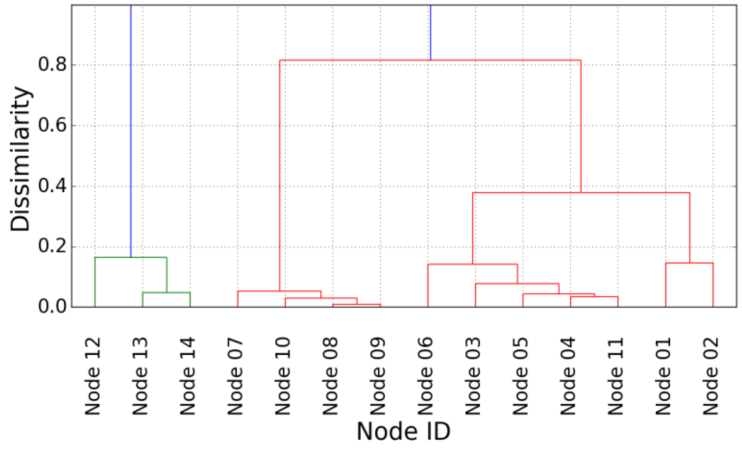


Figure 6 Dendrogram for clusters produced network with modified line lengths

Once the clustering has been performed the next step is to divide the network into cells. In this simulation based experiment, the two networks have been divided into two and three cells (as shown in Figures 7 and 8). The idea here is to validate the clustering process for cell creation for voltage regulation purposes. It is important to understand the impact of network topology when defining cell boundaries.

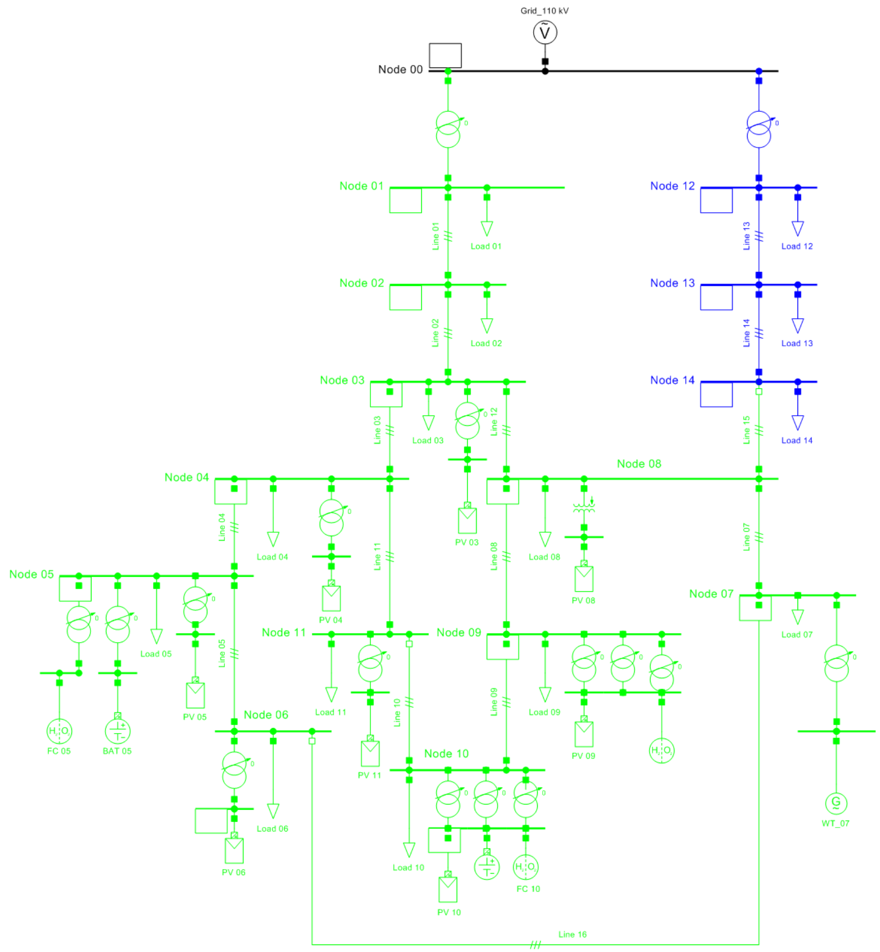


Figure 7 The CIGRE medium voltage network

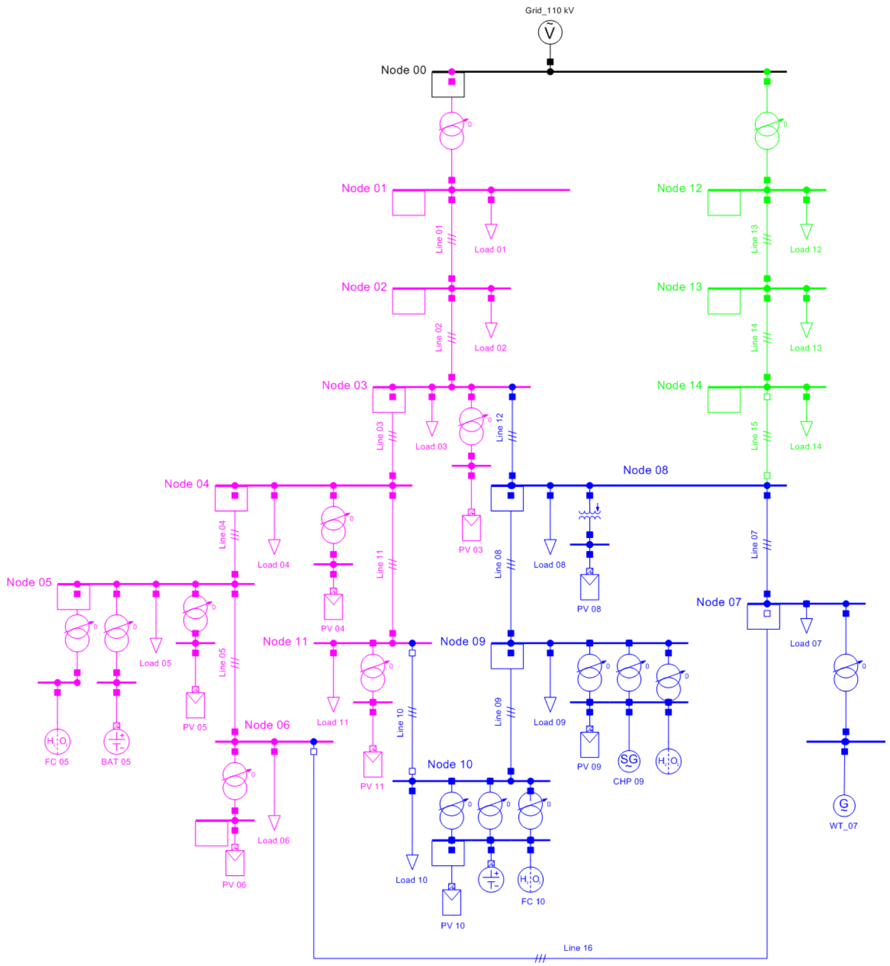
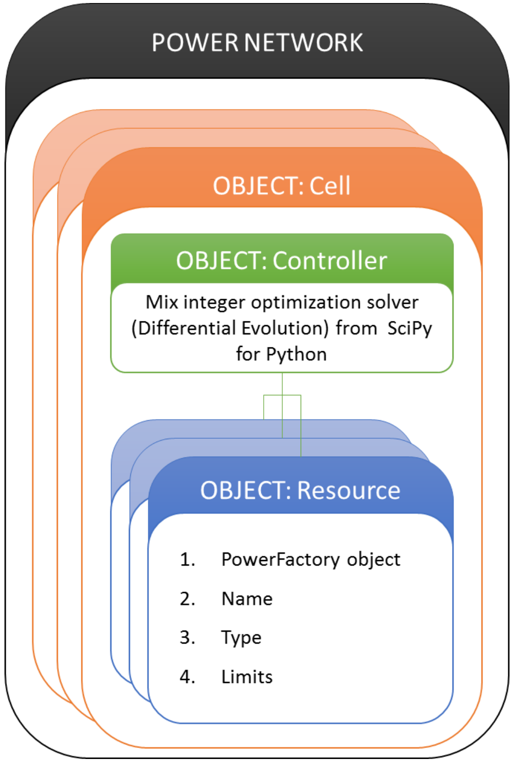


Figure 8 The modified CIGRE medium voltage network

C) Simulation setup overview

Once the clusters have been identified and the cells have been created next step is to create an autonomous independent coordinating controller for each of the zones. In the final step, the simulation results for the cell based optimal power flow (CBOPF) are to be compared to three other scenarios

	namely QDS with no control, QDS with local var control and the centralized OPF. The sensitivity of voltage regulation capability and the objective function to the number of cells formed is important to understand. Figure 9 given a graphical overview of the overall simulation process. An instance of PowerFactory has been created using the Python API provided by DIgSILENT. Within the network, multiple cell objects have been created (one for each cell). Each cell object can have multiple resource objects. These objects correspond to controllable VAR devices connected within the cell boundary. These resources can have both continuous (e.g. PV inverters) or discrete (e.g. Transformers) operation. Within the resource object, operational limits for each resource should also be defined. Finally, a coordination controller object within the cell object is responsible for calculating the new optimal set points for the resources connected with the network. The coordinating controller uses a differential evolution solver provided by SciPy. Each cell controller runs autonomously and independently.  **Figure 9** Python code overview

Precision of equipment	*For the components of the lab equipment the precision is given such that the experiment's uncertainty can be derived.*
Uncertainty measurement	*Based on the precision of equipment of the lab instrument and of measurement algorithms, the parameters to model the measured quantities' errors are provided it is specified how experiment's uncertainty can actually be measured.*

Experiment Reporting 3.4.1

<table>
<tr><td>Title</td><td>Simulation of PVC+PPVC with CIGRE MV test grid</td></tr>
<tr><td>Ref. Experiment Spec.</td><td>Experiment Specification 3.4.1</td></tr>
<tr><td>Test Criteria</td><td>

- Optimal cell division for voltage control
- TCR28: Minimum power losses in the cell
- TCR30: Safe and robust voltage for all nodes

</td></tr>
<tr><td>Results</td><td rowspan="2">

Once the clusters have been identified and the cells have been created next step is to create an autonomous independent coordinating controller for each of the zones. In the final step, the simulation results for the cell based optimal power flow (CBOPF) are to be compared to three other scenarios namely QDS with no control, QDS with local VAR control and the centralized OPF. The sensitivity of voltage regulation capability and the objective function to the number of cells formed can be an interesting study. In the first set of simulation studies the chosen network has been divided into 2 and 3 zones. It is imported to note that for this initial set of simulations, the network topology parameters are unchanged. In the normalized electrical distance plot, it was shown that the network has strong voltage dependence due to the fact that the lines at the beginning of the feeders are longer and the lines towards the end of the feeder are relatively much smaller. Due to this reason, it is unfeasible to divide the network into more than two zones.

2 Cells

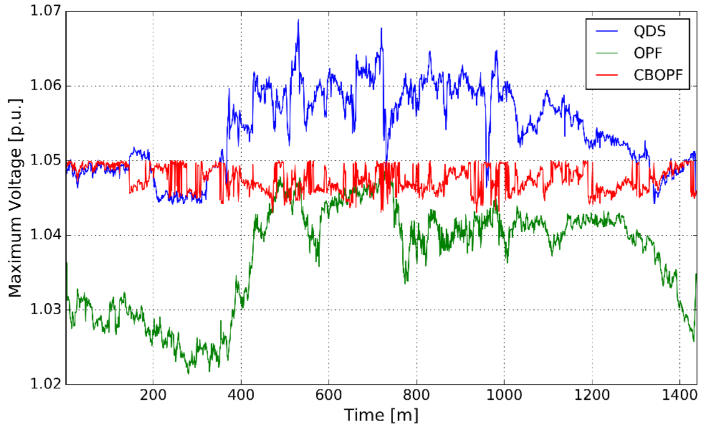


Figure 10 Maximum voltage in the network for the three scenarios

</td></tr>
<tr><td>Discussion / Open Issues</td></tr>
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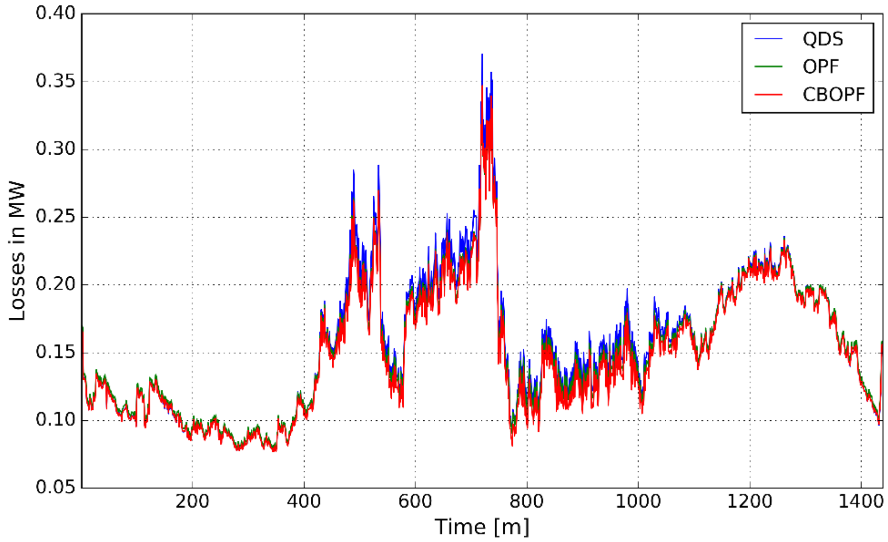


Figure 11 Total network losses for the three scenarios

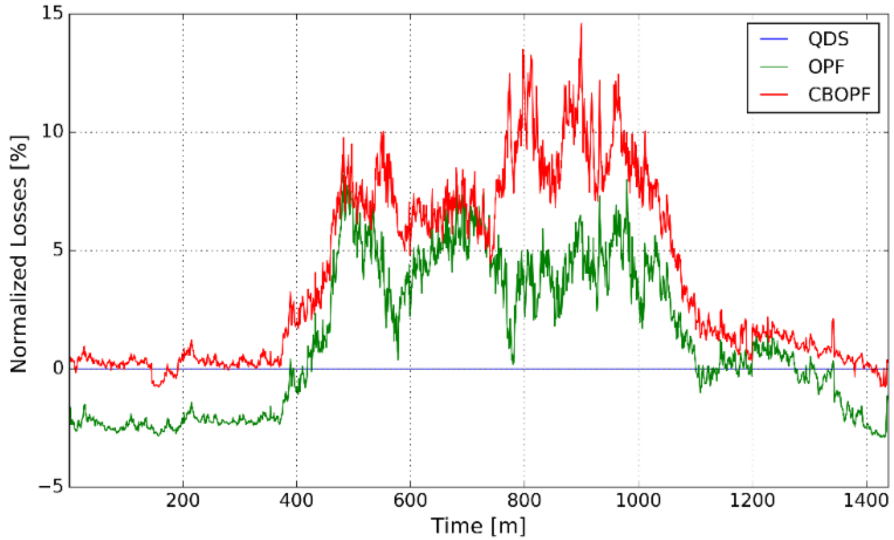
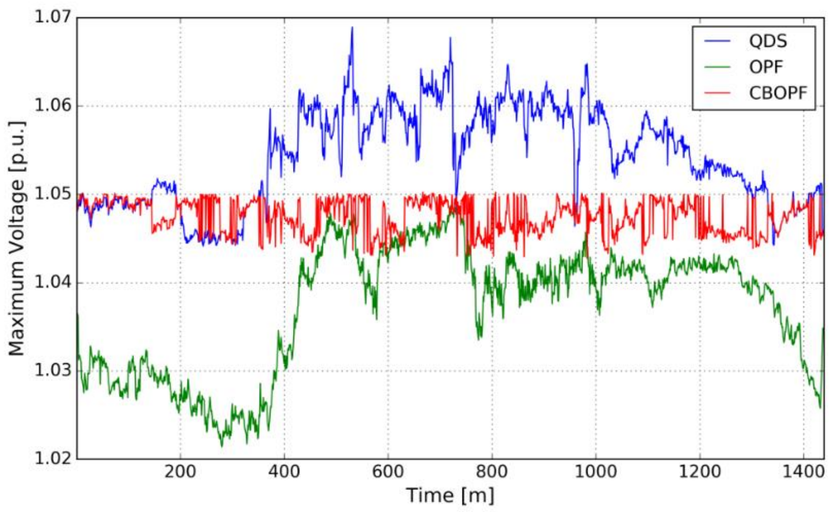
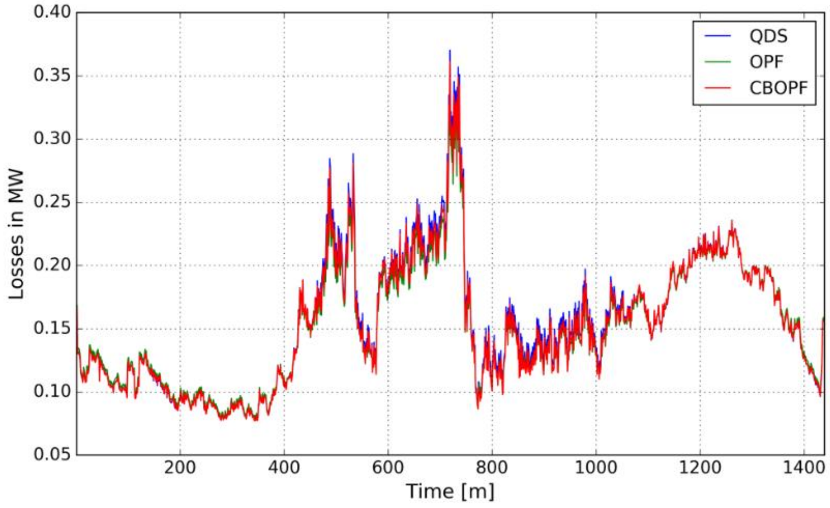


Figure 12 Normalized losses for the three scenarios

	3 Cells  **Figure 13** Maximum voltage in the network for the three scenarios  **Figure 14** Total network losses for the three scenarios

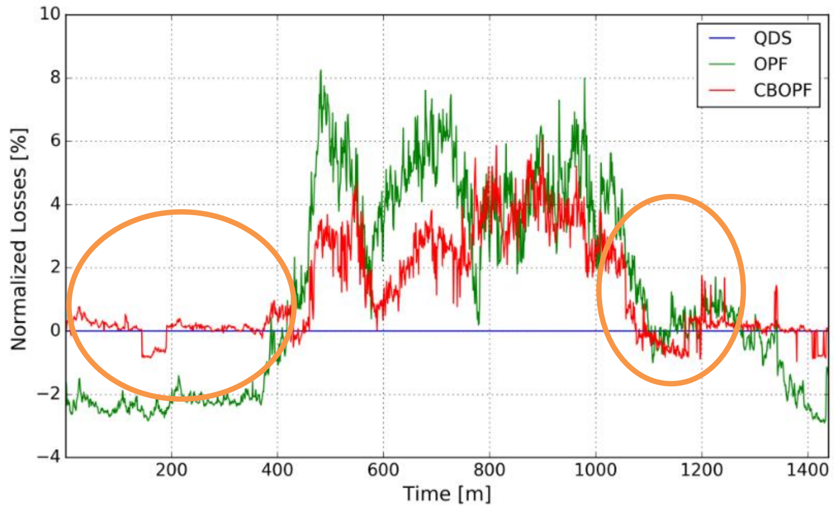


Figure 15 Normalized losses for the three scenarios

The simulations results show that implemented simulation setup does well to mitigate system losses while ensuring voltage boundary is not violated. This is true for 2 and 3 cells implemented. The CBOPF for the 2 cells performs well and reduces losses by more than 12 % when compared to QDS results. For the 3-cell case however, the peak reduction in losses decreases to about 6%. This is a result of strong voltage dependence between neighbouring cells that leads to incorrect set point calculation.

In the second set of simulation studies the network with modified line lengths has been divided into 2 and 3 zones. The network has been modified to impress upon the utility of the cell based approach and to validate the method for defining cell boundaries.

2 Cells Modified

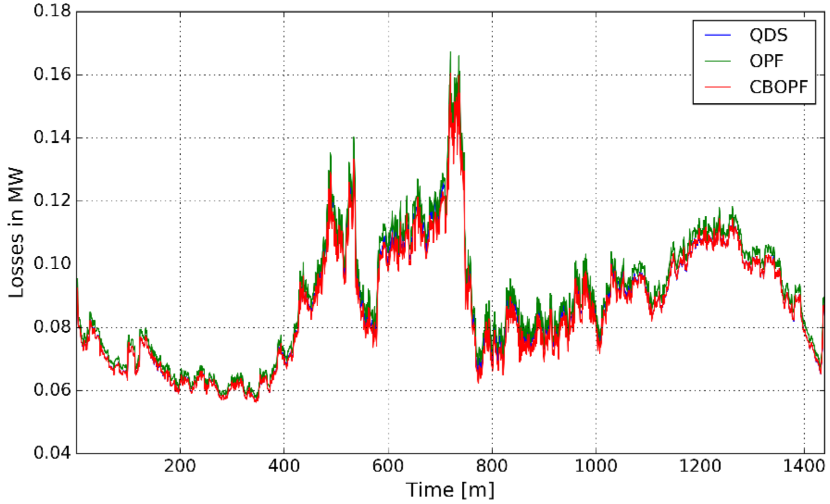


Figure 16 Total network losses for the three scenarios

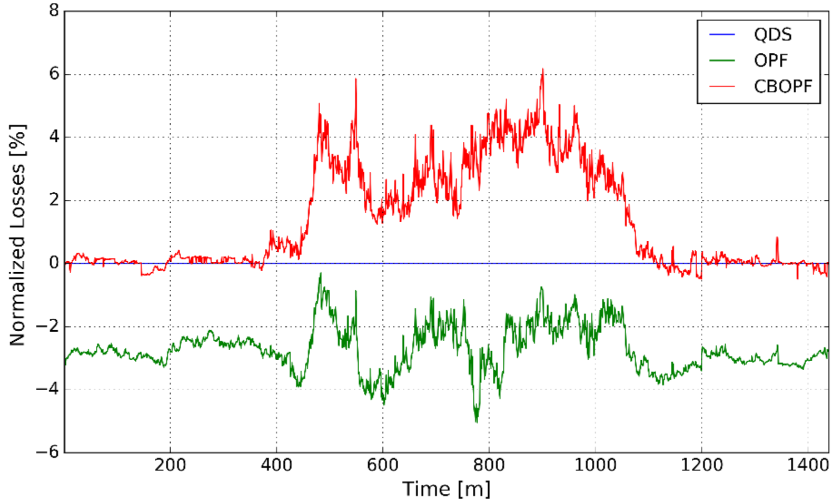


Figure 17 Normalized losses for the three scenarios

	3 Cells Modified

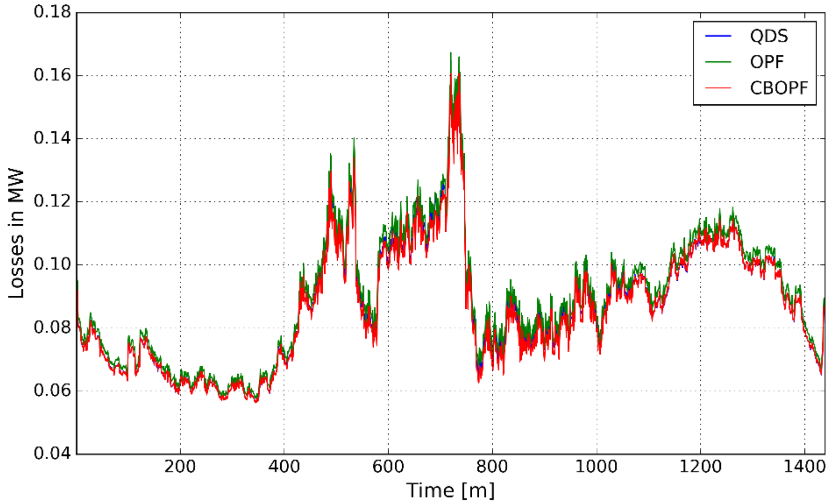


Figure 18 Total network losses for the three scenarios

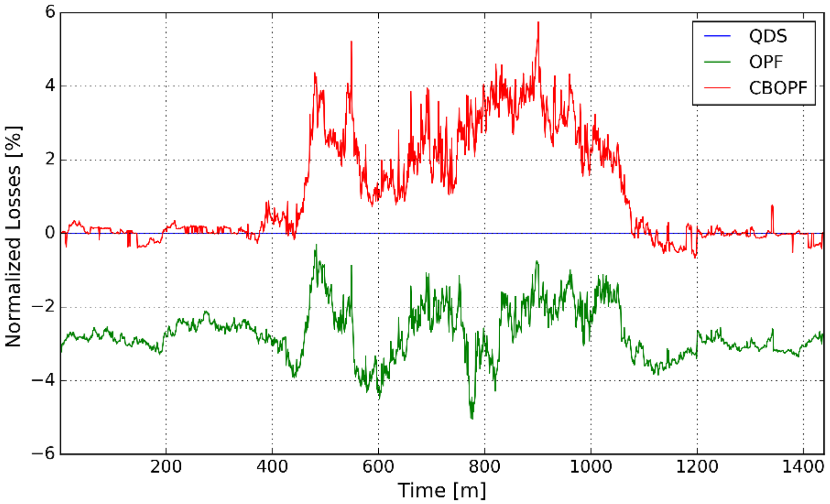
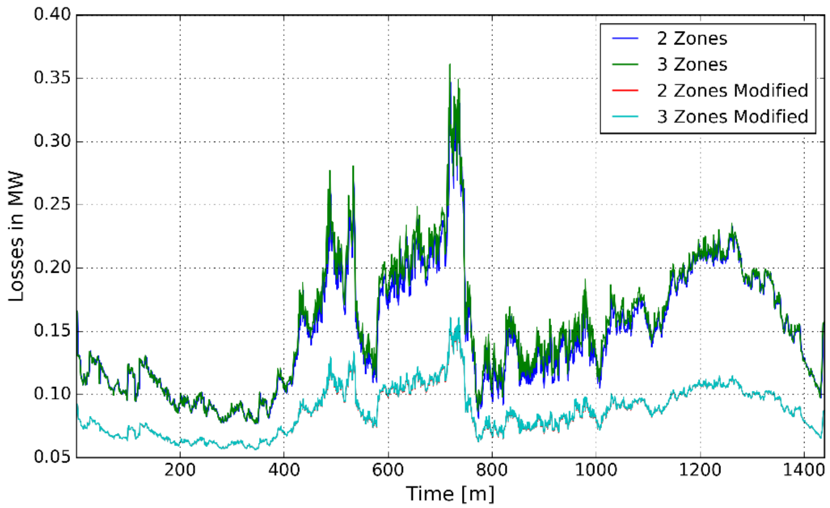


Figure 19 Normalized losses for the three scenarios

	For the modified network with 2 cells, the max decrease in losses compared to base case (QDS) is about 6%. The results for 3 cells are comparable to 2 cell results and the peak decrease in losses is again approximately 6%. The coordinating controller for each cell has information contained within the cell. And hence converges to local minima which may be different from the global minima. In the first set of simulation based experiments a network with strong voltage interdependency was divided into 2 and 3 cells. It has been shown that if neighbouring cells have strong voltage coupling, they interfere with each other's operation and the local optima might be significantly different from the global minima. In the second set of simulations, the chosen network has weak voltage interdependence therefore, increasing the number of cells has little impact (compared to the previous case) on loss minimization. **Comparison**  **Figure 20** Total network losses for the three scenarios

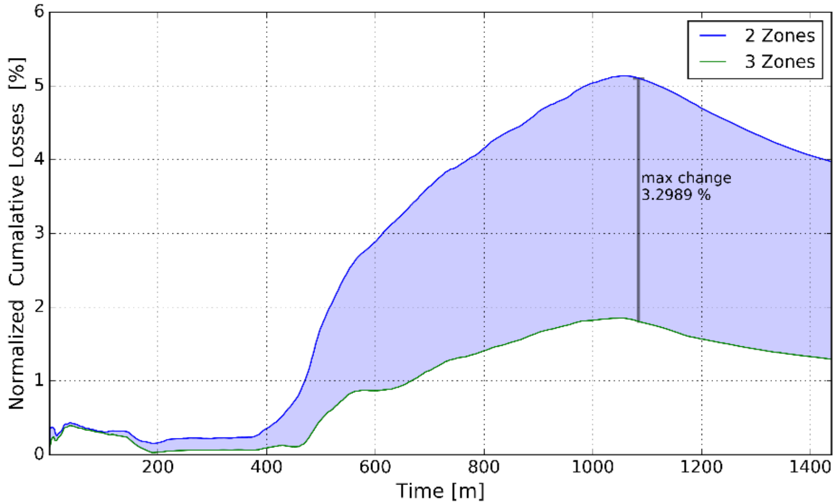


Figure 21 Normalized losses for the three scenarios

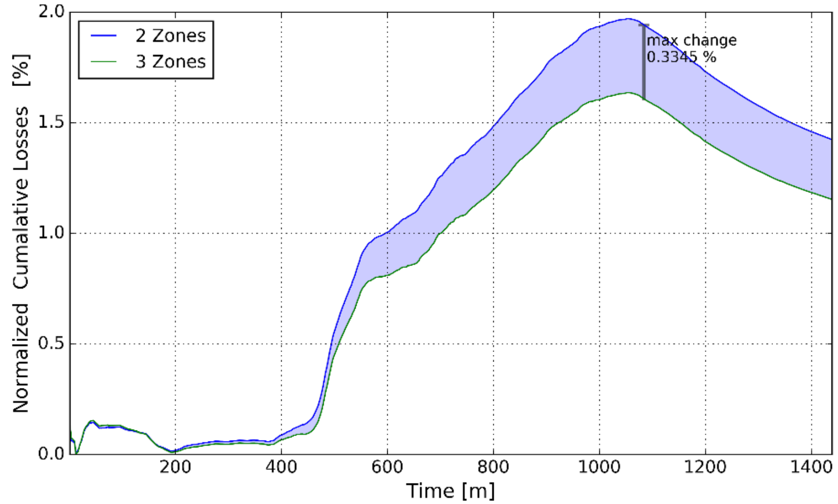


Figure 22 Normalized losses for the three scenarios

	The final results show that if we increase the number of cells from 2 to 3 for the first network, the total normalized losses reduce from 4% to 1.4%, with the peak difference being 3.29%. For the second network however, the degradation is much lesser (0.25%) at the end of the day's simulation.
Lessons Learned	● WoC concept and covered integrated use cases (control/observable functions) – Clustering approach using the normalized electrical distance provides a suitable tool for the identification of ELECTRA cells – Simulation experiment show the successful operation of the ELECTRA voltage control in context of the WoC – Around 6% decrease in loses can be observed for the used testing scenario compared to the base case – The ELECTRA voltage control approach is also suitable to be used for traditional distribution grid optimization ● Validation environment – PowerFactory simulation and Python scripts where very useful to implement the experiment – With the object-based realization (i.e., Figure 9) the approach can be easily extended to larger test grids with more cells

Test Specification 3.5

ID / Title	Hardware-in-the-Loop based proof-of-concept analysis of the PVC+PPVC use case incl. a selected number of DER units (PV system, Energy Storage Systems, etc.), sensitivity analysis
Ref. Test case	Test Case 3
Responsible Entity	AIT
Experiment Type	Coupled HIL co-simulation
Test System (also graphical)	Same as for Test Specification 3.4
Research Infrastructure	AIT SmartEST Laboratory
Input parameters	• Generation profiles • Load profiles • Grid topology • Tie-line exchanges • DER controllers parameters
Output parameters	• Power losses • Node voltages
Target measures	• Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes
Test Design	Comparison of different cell-configurations and different OPF implementations; usage of a real converter controller
Initial system state	*Description of conditions that are prerequisites to actually run the test and initial choices of parameters.*
Evolution of system state and test signals	*Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds); incl. variability attributes*
Other parameters	*Information of data that should be tracked apart from the input and output parameters and system state, test signals*

Storage of data	*In which format are the parameters stored?*
Temporal resolution	*Discrete or continuous simulation and (if applicable) resolution of the discrete time steps*
Source of uncertainty	*In order to evaluate the quality of the test, the possible sources of uncertainties are given in how they can be quantified.*
Suspension criteria / Stopping criteria	*Under which conditions are the test results not valid or the test is interrupted*

Experiment Specification 3.5.1

<table>
<tr><td>Title</td><td>HIL co-simulation of PVC+PPVC with CIGRE MV test grid</td></tr>
<tr><td>Ref. Test Spec.</td><td>Test Case 3, Test Specification 3.5</td></tr>
<tr><td>Research Infrastructure</td><td>PowerFactory, Python API, Python Scripts, AIT Smart Grid Converter “ASG-Converter” (emulated power electronics + real converter controller), Typhoon HIL real-time simulator, InfluxDB, Grafana</td></tr>
<tr><td>Experiment Realisation</td><td>HIL co-simulation</td></tr>
<tr><td>Experiment Setup
(concrete lab equipment)</td><td rowspan="2">1. Overview of the Coupling Concept

The proposed concept of a real-time co-simulation environment which is being used for evaluating complex power system applications is mainly based on three elements. As depicted in Figure 23, the coupling framework has to provide a real-time signal exchange between automation and control applications (referred to as “Simulation” in Figure 23), the power grid simulation (i.e., “Grid” in Figure 23), and hardware components coupled to it (i.e., “Grid” in Figure 23). It has to be noted that each component may provide different interfaces for the coupling of the tools which may also be implemented with different programming languages. Therefore, a coupling approach is required, which guarantees a real-time signal exchange between the aforementioned elements. Since different simulation tools, controller hardware and software as well as real power system components (e.g., inverter-based distributed energy resources) may need to be coupled, the corresponding framework must be designed in a proper way. Synchronization and the provision of proper interfaces to those tools and components are the main requirements for such a framework, where a prototypical realization is introduced below.

Figure 23 Concept for coupling simulators and hardware components</td></tr>
<tr><td>Experimental Design and Justification</td></tr>
</table>

2. Prototypical Realization

Considering all mentioned requirements and needs for coupling, the use of a virtual bus-system as a synchronization and interfacing concept can provide a synchronized signal exchange between the coupled tools. Such a concept is realized by the so-called LabLink approach which has especially been developed for coupling and interfacing simulation tools and power system laboratory components in a flexible and extensible way. This middleware approach provides the possibility to connect different tools via Python or Java interfaces. As outlined in Figure 24 at the core of LabLink is a MQTT Broker. LabLink clients connect to the broker and communicate with each other via the publish and subscribe paradigm. The client communication is event based and asynchronous. A synchronisation client (Synchronisation Host) coordinates clients in a simulation to have a common time base. After defining the simulation parameters in a corresponding configuration file, the Synchronization Host has the specification of the required and additional clients and their needs for the simulation.

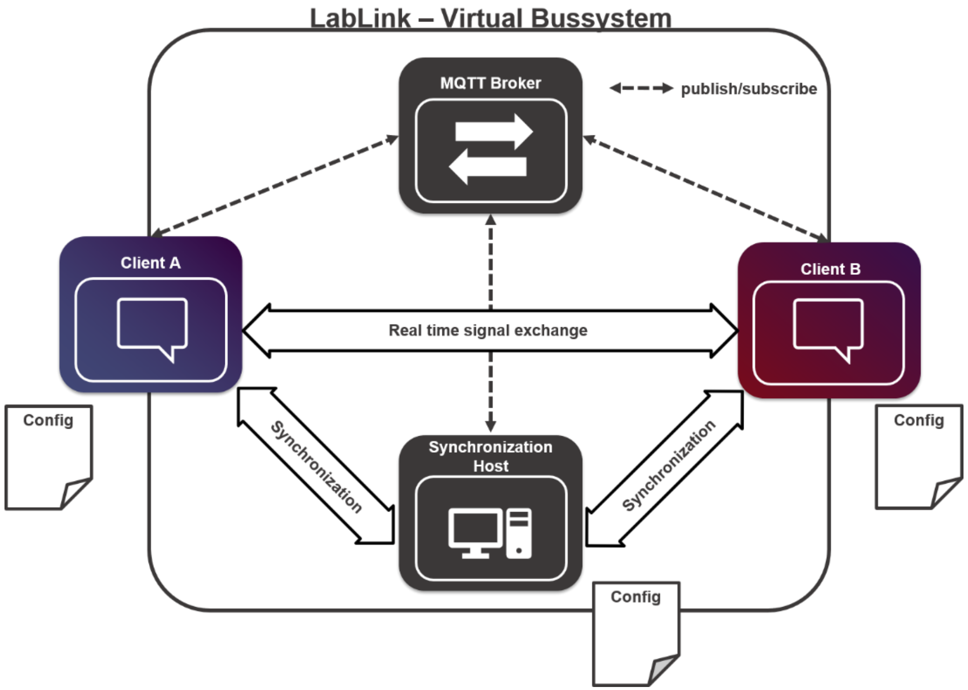


Figure 24 Realization of the coupling of tools using the LabLink framework

	The interface of the clients is equal, whereby only the interface for the subscriber (e.g. hardware, databases, or another software) has to be implemented. Each client is able to provide data as well as consume them from other clients. On this basis, a co-simulation validation environment has been realized in this work based on LabLink where the following five clients are being connected (see Figure 25) in order to validate complex power system applications as outlined above: ● *Typhoon HIL Client:* Typhoon HIL as a DRTS for emulating and validating hardware components (e.g. whole converter concepts, converter control) providing software and hardware interfaces. In this work the Typhoon HIL Python API was used to exchange signals (node voltages, currents, etc.) between a large-scale power grid simulation and an emulated converter device (in Typhoon HIL DRTS) via LabLink. ● *Simulation Client:* This Client—which usually contains automation and control algorithms (e.g., cell-based voltage control in case of ELECTRA IRP)—directly uses the API of the connected power system simulator PowerFactory. Due to the fact that this API is not usable for more than two subscriber or multiple threads at the same time, the simulation and the PowerFactory Client are combined into one multithreaded LabLink client which uses the PowerFactory API in a single threaded manner. ● *PowerFactory Client:* PowerFactory supports several interfaces. The Python API is an ideal fit for the LabLink environment Python bindings. This client can provide all data points (node voltages and currents, frequency, active and reactive power, etc.) of each grid component and is able to consume data from other clients (set-points for active and reactive power to converter-based generators), which are being published via LabLink. ● *InfluxDB Client:* Stores and archives timestamped data points published by other LabLink clients (e.g., Typhoon HIL, PowerFactory). The simulation results stored in this database can be monitored, e.g., by Grafana (a web-based dashboard visualization software for timestamped metrics). Thus, a live monitoring of the power systems application can be realized. ● *Synchronization Client:* Contains all simulation parameters (duration, time-resolution, connected clients, etc.) and it differs from the other mentioned clients how it is specified and implemented. The Synchronization Client is mainly defined by configuration files containing the mentioned simulation experiment parameters. All clients (except the Synchronization Client) have the same configuration structure which defines LabLink communication metadata.

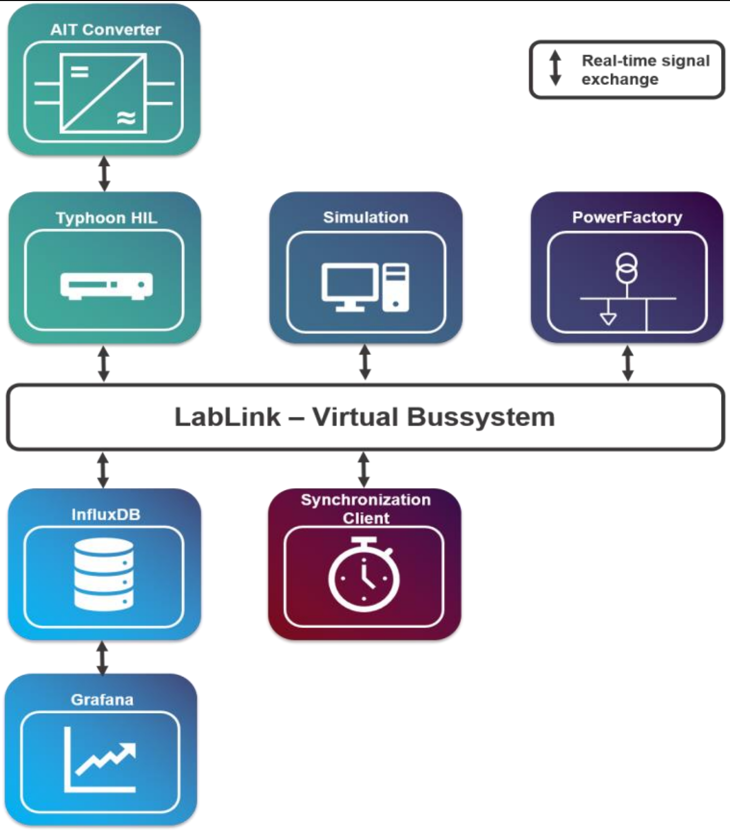


Figure 25 HIL co-simulation based validation set-up

3. Used Test Scenario

For the simulation two parts of the environment are mainly on focus. On the one hand the power system control application (Cell-based Simulation Client) and on the other hand the emulated ASG-Converter (Typhoon HIL with ASG-Converter connection). To fit the converter in to the grid, a definition of the role of the converter is necessary. Figure 26 shows a particular feeder of the CIGRE MV network (same as for Experiment Specification 3.4.1; i.e., modified version with 3 cells) where PV 09 is placed in an low Voltage area of Cell One. This random chosen PV-Object will be deactivated in PowerFactory and instead the ASG-Converter emulation takes place as an HIL co-simulation. Each of these zones should have at least one controllable device.

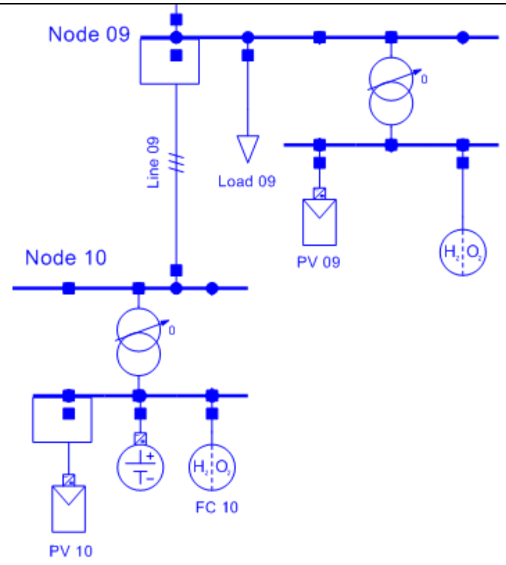


Figure 26 Extract of the Cell-based grid with P V 09

The DC side (Photovoltaic) of the converter needs to be replaced by a Python script.The corresponding real-time simulation model in Typhoon HIL, which is connect via LabLink and the corresponding clients is depicted in Figure 27. The model contains the PV array, DC measurements, the DC-AC converter, the interface device, grid measurements, and parts of the test feeder which is connected to the grid simulation in PowerFactory. Moreover, the real converter controller (i.e., embedded controller) is connected to the DRTS.

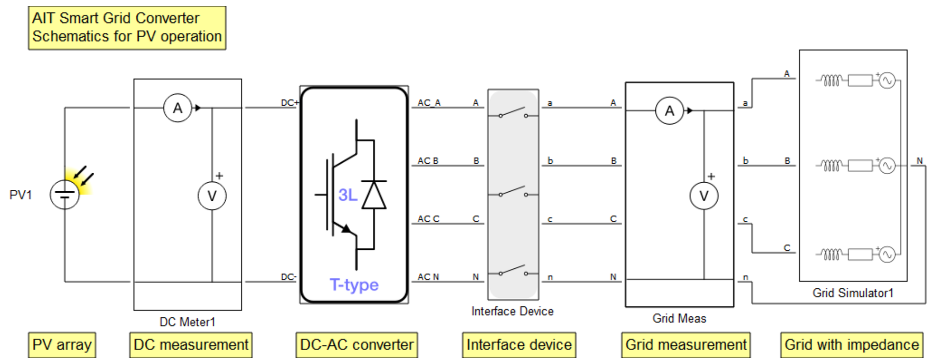


	Figure 27 Converter model in Typhoon HIL The big advantage of this set-up is the possibility to connect the real implementation of the converter controller instead of deriving a less precise component model for the grid simulation which may need a lot of resources to be developed and validated. **4. Realized Test** As described above the Synchronization Client needs all the simulation parameter for the Synchronization Host. The implemented test includes a one day simulation within one minute step-size. All mentioned clients from Figure 25 are required and no additional clients are implemented. Furthermore, the ASG-Converter will have a signal exchange via LabLink with Node 21 of the grid. Due to the balanced configuration of the three phases, only one voltage data-point of the grid is necessary. A “Cell” object is created for each “ElmZone” defined in the PowerFactory project file. Each Cell “Object” is created for each controllable device connected within the zone. Properties for each object are populated (required for optimization). The cell controller implemented in Python use external solver (Differential Evolution available in SciPy library). PowerFactory has been mainly used as a load flow engine for this proof-of-concept validation.
Precision of equipment	*For the components of the lab equipment the precision is given such that the experiment’s uncertainty can be derived.*
Uncertainty measurement	*Based on the precision of equipment of the lab instrument and of measurement algorithms, the parameters to model the measured quantities’ errors are provided it is specified how experiment’s uncertainty can actually be measured.*

Experiment Reporting 3.5.1

<table>
<tr><td>Title</td><td>HIL co-simulation of PVC+PPVC with CIGRE MV test grid</td></tr>
<tr><td>Ref. Experiment Spec.</td><td>Experiment Specification 3.5.1</td></tr>
<tr><td>Test Criteria</td><td>● Optimal cell division for voltage control
● TCR28: Minimum power losses in the cell
● TCR30: Safe and robust voltage for all nodes</td></tr>
<tr><td>Results</td><td rowspan="2">During running the co-simulation, the behaviour of the mentioned cell-based power system control application are able to be monitored. The test confirms the real-time signal exchange between the clients. Regarding to the SCADA-system in Figure 28 the overview of the Typhoon HIL proves that the voltage of the PowerFactory simulation grid successfully achieved the Typhoon HIL (data-point “Van_Grid” in section “Grid Side”) After sending the signals to the ASG-Converter, the Typhoon HIL DRTS received the signals from the converter (i.e., the active and reactive power are the “P” and “Q” values on the illustrated power display).

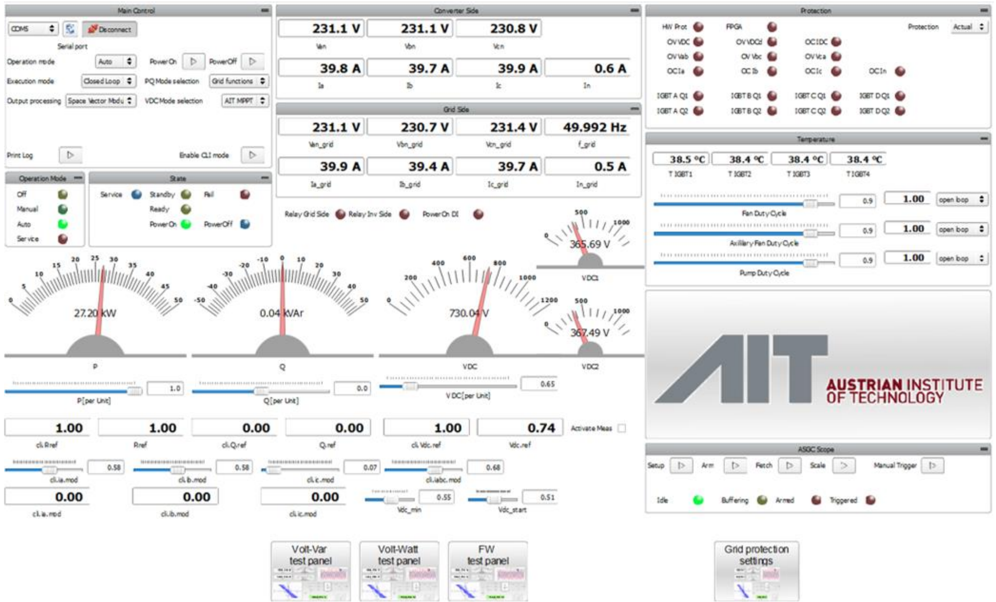


Figure 28 SCADA UI for controlling the ASG-Converter

As a further result the database (i.e, InfluxDB Client) consumes all data-points, which are published via LabLink. With the second monitoring software (i.e., Grafana), which is directly connected to the</td></tr>
<tr><td>Discussion / Open Issues</td></tr>
</table>

database (see Figure 25), the whole simulation signal exchange is displayed. In Figure 29, the voltage (first graph) and the reactive and active power (second graph in load-reference arrow system) are displayed. The voltage of the node reaches up to 238 Volt. Thereby the Q = f(U) control algorithm of the ASG-Converter provides a phase shift. As a further proof, the Synchronization Host guarantees the real-time signal exchange, which can be seen in the live monitoring as well. On this occasion, long time periods (approximately 30 s) after 15 simulation steps are also monitored, which are based on the global numerical optimization of the cell-based simulation and has, due to the Synchronization Host, no effect on the real-time signal exchange.

Figure 29 SCADA UI for controlling the ASG-Converter

Furthermore, the WoC voltage control approach leads to the achievement of a comparison between the different amount of ELECTRA cells. As presented in Figure 30, the network losses can be reduced by defining more cells, including the PPVC controller. Also, the impact of the line length shows a big influence on the normalized electrical distance approach for these cells. As outlined in Figure 30(b) the normalized losses were able to improve by a maximum change of 3.30 %.

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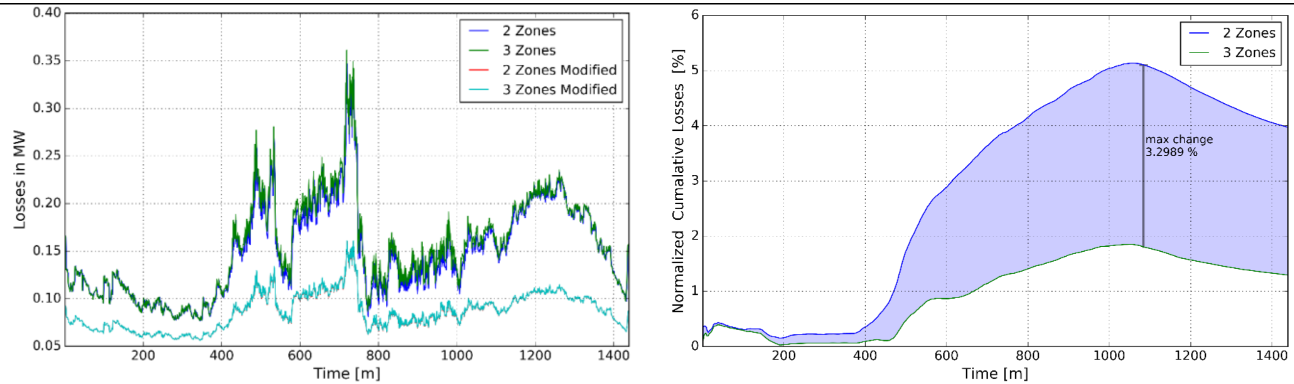
<td>

(a) (b)
Figure 30 Network losses for the three scenarios: (a) total losses, (b) Normalized losses</td>
</tr>
<tr>
<td>Lessons Learned</td>
<td>

WoC concept and covered integrated use cases (control/observable functions)

The coupled simulation and HIL experiment shows the successful operation of the ELECTRA voltage control in context of the WoC approach.
Around 6 % decrease in loses can be observed for the used testing scenario compared to the base case and the ELECTRA voltage control approach is also suitable to be used for traditional distribution grid optimization.

Validation environment

For this validation case, real-time co-simulation with HIL coupling was a very helpful tool for carrying out the proof-of-concept evaluation using a real component controller.
The validation demonstrates a high number of possibilities and powerful flexibility for the simulation environment. Within this conclusion several LabLink Clients can participate in the co-simulation, whereby the complexity of a large-scale communication model will be simplified.

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Fact Sheet for Test Case 3

Brief summary/answer to research question(s)

Integration and Validation of

Scenario

This validation scenario addresses the proof-of-concept evaluation of the ELECTRA IRP voltage control schemes (PVC + PPVC) of the distributed, real-time Web-of-Cell (WoC) control concept.

The objective is to test the correct operation of the voltage control algorithm's for MV/LV distribution grids in rural areas with a high amount of renewable generation by using components from the AIT SmartEST lab.

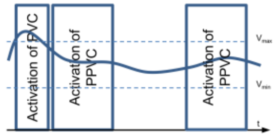

Fig. 1. Operation of the PVC/PPVC

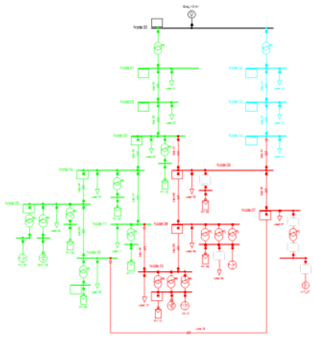

Fig. 2. CIGRE MV test grid represented in the WoC framework (3 cells)

Research Questions

- How can ELECTRA cells be identified? What are optimal configurations for them?
- What is the impact of the of cell division on the operation of a determined network?
- How can parameterization errors (e.g., droop control settings) of inverter-based Distributed Energy Resources (DER) be identified and represented in future control room scenarios?

Operational Parameters

Software simulations, real-time hardware- in-the-loop co-simulations based on:

- Involvement of 2-3 cells (i.e., single cells; based on CIGRE MV test grid)
- High-penetration of distributed, renewable generation (i.e., inverter-based DER – mainly wind and PV)
- Loads, tie-lines, tap-changing transformers

Key Performance Indicators (KPI)

Criterion	Definition
Optimal cell division for voltage control	Optimal configuration of a cell for voltage control taking local resources (generators and loads) into account
Safe and robust voltage for all nodes	The voltage setpoints are within deadbands with additional margins in order to avoid undesirable (excessive) OPF calculations
Minimum power losses in the cell	Network losses [kWh]: sum of all real power generated in a cell and/or imported from other cells minus all real power consumed by cell loads in the evaluated period

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Identification of Cells

- Identification of potential cells using the normalized electrical distance approach
- Clustering and selection of suitable cells (with sufficient flexibility)

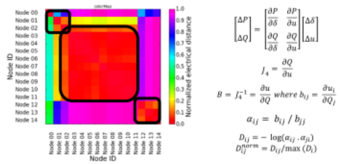

Fig. 3. Colour plot of the normalized electrical distance matrix for the CIGRE MV test grid

Hardware-in-the-Loop (HIL) Test

- Integration of emulated inverter-based DER (i.e., AIT Smart Grid Converter - ASGC)
  - Full four quadrant operation
  - Immediate and frequency control services
- Realization of a real-time co-simulation/HIL experiment using
  - Grid simulation and control algorithm execution in PowerFactory (with Python API)
  - ASGC emulation in Tyhoon-HIL (power electronics, grid connection) and real controller board (PVC)
  - Coupling of tools via AIT LabLink framework

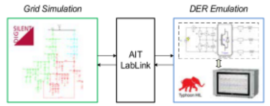

Fig. 5. Coupling via AIT LabLink

- Dashboard-based control room visualization (e.g., voltages, DER parameterization errors)

Fig. 6. Control room visualization

Simulation-based Validation

- Implementation of CIGRE MV test grid (different versions with modifications resulting in 2 and 3 cells configuration) in DIgSILENT PowerFactory
- Voltage control algorithms and optimization implemented in PowerFactory and Python
- Comparison of ELECTRA with centralized voltage control approach (base case)

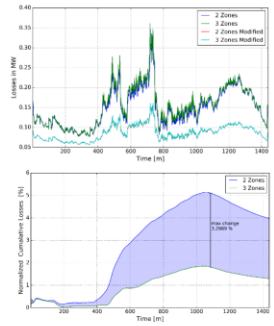

Fig. 4. CIGRE MV test grid simulation results with 2 and 3 cells

Conclusions & Lessons Learned

- Clustering approach using the normalized electrical distance provides a suitable tool for the identification of ELECTRA cells
- Simulation and HIL experiments show the successful operation of the ELECTRA voltage control in context of the WoC
- Around 6% decrease in loses can be observed for the used testing scenario compared to the base case
- The ELECTRA voltage control approach is also suitable to be used for traditional distribution grid optimization
- Real-time co-simulation was very helpful for carrying out the validation experiments

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