Rapid Control Prototyping Platform for Networked Smart Grid Systems

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***Abstract*—With the progress of the smart grid development and the prototyping of active control solutions supporting grid operation in the presence of a large amount of distributed generators, a design methodology for networked smart grid systems is required. This paper proposes an approach for fast system simulation and emulation-supported prototyping. A distinct tool, the Simulation Message Bus, accompanies the development of distributed controllers for power distribution grids from concept to field application. With this, the idea of an integrated development tool chain as it is known e.g. in the semiconductor or car industry is brought to the energy domain.**

I. Introduction

The international development of Smart Grids can be roughly described in four phases: in the first and early phase, the basic ideas such as algorithms for demand side management, active control of distributed generators, integration of storages and others were formulated. The guiding question was: what concepts do we have for future electrical energy systems? In a second phase, different kinds of organisations that foster stakeholder interaction have been evolved such as the GridWise alliance in the U.S. [1], the NEDO Smart Grid activities in Japan [2], the European Technology Platform Smart Grids [3], or other national platforms such as the Austrian Smart Grids Technology Platform [4]. The question in that phase was how the relevant stakeholders, typically power grid operators, industry, end-users and researchers, can efficiently work together to solve the challenges of renewable integration, aging infrastructure and others. These activities have led to the current phase that focuses on a number of smart grid demonstrations in many countries of the world. A critical mass of Smart Grids realisations have come together, which answer the question of how a real-world Smart Grid can look like. The guiding question of the upcoming fourth phase is now: How can the prototype experiences from Smart Grid demonstration be transferred into commercialisation of Smart Grid components and systems?

This work focuses on the last question by proposing a rapid control prototyping platform for networked Smart Grid systems that supports the development and testing of smart grid controllers for real-world applications. This shall be shown using the example of a control unit allowing coordinated voltage control with tap-changer transformers and reactive power management of inverters for low voltage distribution systems. The latter is developed in the frame of the Austrian research project *DG DemoNet – Smart LV Grid* [5]. As complex and heterogeneous as low voltage distribution grids can be, so the according control concept development is. Today, no widely-used test systems for Smart Grid controls development exist, as they do in other technical domains such as automotive industry or industrial machines. As the power grid itself has to be highly available, it is not possible to use real grid segments as development environment. The only way to go is to start with the controls development in simulation and proceed with the complex and error-prone porting of the algorithms to hardware in the field. This paper presents a consistent and seamless way for Smart Grid controls development, starting with the control concept, throughout the whole development, testing, and evaluation process right up to the final control application in the field.

II. Methodology and Approach

The method proposed in this paper is to support the prototyping process or control entities in a networked Smart Grid system with a supporting tool. For coupling these entities which are used in a control prototyping platform a so called Simulation Message Bus (SMB) was introduced and briefly described in [6]. The approach has been developed and verified in the context of the development for a smart low voltage grid controller from concept to field test validation. The SMB is designed as a stand-alone server component which will route messages between clients much like a network switch. It supports the connection of an arbitrary number of such clients, and acts as the central message hub for the entire simulation. The principal architecture, illustrating the components of the SMB, is depicted in figure 1.

The SMB holds a number of channels, which serve as I/O points for connecting clients. When configuring the SMB before startup, each channel is defined with a unique ID. This ID allows the SMB to route incoming packets according to predefined routing tables, rule sets and packet inspection. Atop each channel sit zero or more proxies, which are pluggable

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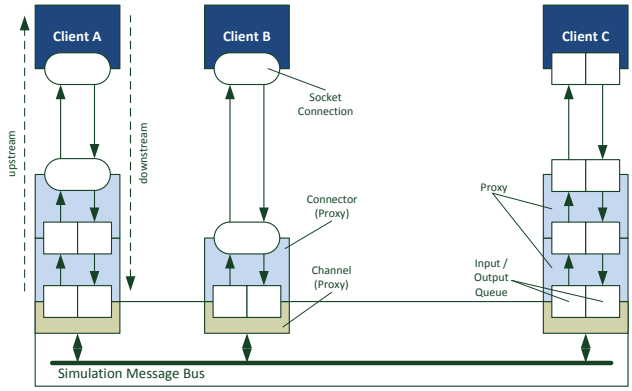

Fig. 1. SMB architecture with three simulation clients

components extending the channel functionality. A proxy has input and output queues on both ends (bottom, which is the end pointing towards the channel, and top) and processing functions for packets passing through either direction (upstream going from bottom to top and vice versa). Proxies can be overridden to create custom functionality. This flexible architecture allows the SMB to be used in all development stages during a fully integrated control development process, that are listed in figure 2:

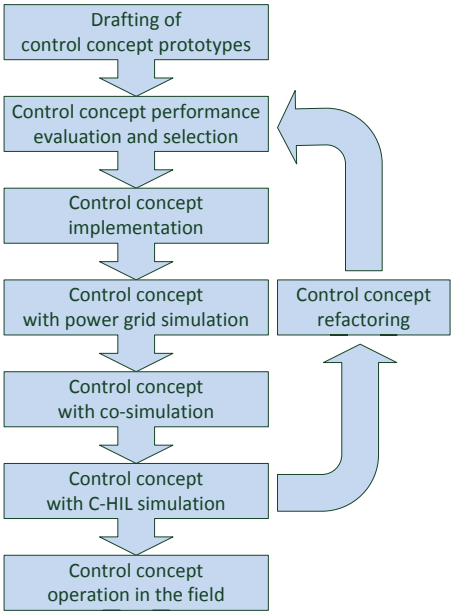

Fig. 2. Control development stages where SMB is used

Going from one development stage to the other the SMB component itself remains the same and only some components have to be replaced or added. The developed controller will remain the same during the whole process. Even in the final control application in the field, the controller does not need to be ported to any other system.

III. State of the Art: Conventional Development Process

In todays low voltage grids there is usually no active control employed. The systems are installed on the basis of experience, utilization factor and worst case estimations, and operated blindly. Due to the introduction of the Smart Grid with its high loads (e.g. electric vehicles) and fluctuating decentralized power generation (e.g. combined heat and power unit, photovoltaics, etc.), also low voltage grids have to be controlled actively in order to be able to operate them according to regulations without high investments into the network infrastructure [7]. There are already control concepts available for high and medium power grid control. All these existing control concepts are individually and manually designed and adopted for the grid's specific needs. The adoption of this control concepts to the low power grid would lead to an extreme increase in component count and thus is not affordable.

In traditional control development, tools like MATLAB Simulink [8, p. 193 ff] are used for modelling the device under control, controller development, as well as for simulation and evaluation of the system. This method is used especially for closed and limited systems like in automotive industry or process automation. During a control development process system boundaries have to be overcome. First of all first concepts have to be transferred to a functional implementation for simulation and evaluation. After improvement and testing in simulation, the control concept possibly has to be ported for hardware in the loop (HIL) tests. Another porting has to be done to deploy the control concept to hardware to be able to use it in the field or in control hardware in the loop (C-HIL) tests. Even if some of these porting can be supported by tools like MATLAB Builder JA – which generates Java-Classes from MATLAB programs – this porting has to be done several times and involves high risk for errors and problems. In industrial automation control concepts are often manually implemented on a programmable locic controller (PLC), configured, and never touched again.

The described development and control concepts are hardly applicable for control concept development for low power distribution grids. Thus a seamless way for rapid control prototyping for networked Smart Grid systems has been developed and will be presented in the next chapters.

IV. Fully Integrated Control Development Process

The subsequent sections describe the typical development stages of networked control systems for power grids and how the SMB can support the development step and integration with previous and succeeding steps.

A. Control Concepts Performance Evaluation and Selection

For most novel control approaches for power grids, be it controllers for a secondary substation tap change transformers or a system for optimal feeder configuration, the first step usually is to model the intended behaviour of the controller in some kind of prototyping environment. Typically, this can be Matlab or similar, an optimisation framework or even only a spreadsheet macro. This first implementation is used to compare multiple solutions for a given problem, evaluate its benefits quantitatively and eventually select one of them for implementation in the field. In most cases, it is not necessary to model all details of the employed algorithm and test environment. In *DG DemoNet – Smart LV Grid*, communications

delays play a role in the system for instance. In this early stage these were however not reflect in the model since a voltage control approach that does not work even in the absence of communication delays will also not work with communication delays. This allows to perform all simulations with a dedicated power grid simulator without the need to couple it with other tools. The SMB only comes into the game in the next step.

B. Control Concept Implementation

Assuming that some kind of proof-of-concept or mathematical modelling has been done as described above, it makes sense to begin with the code base for the actual control concept implementation on the intended platform. It is essential in this early phase to have a minimal but workable model of the physical environment available. For a first code prototype, useful input data has to be provided by the platform, which can be used to feed the control system and test its behaviour. On this level of the design, the data set should be still very limited so that it can be overseen by the programmer. However, in order be able to generate re-usable code it is essential that the software interfaces over which input and output data are transferred are those of the intended real-life application. By using the SMB already in this early stage, this precondition can be fulfilled (see also Fig. 3). Message handling will not change over the lifetime of the project, and the associated threading architecture of the program (receiving threads, message buffers, worker threads, sending threads) can also be determined in the beginning of the process. In case of *DG DemoNet – Smart LV Grid*, input data from different voltage sensors in a low voltage grid and an actuator output to step the transformer up and down could already be implemented in this step in the same way as it will work in the final application.

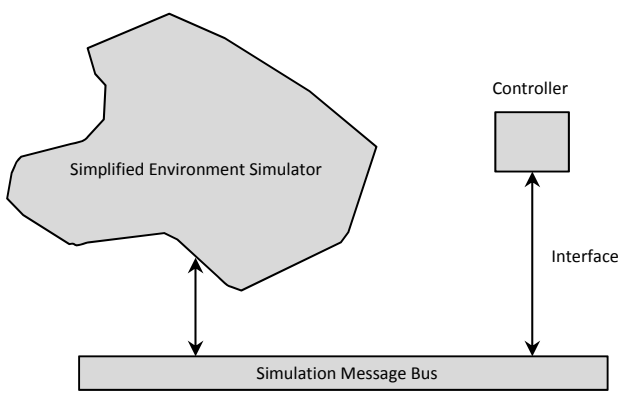

Fig. 3. In the phase of control concept implementation, usage of the SMB helps to introduce useful interfaces to the environment and maintain these through the development process.

C. Control Concepts with Grid Simulation

The simulation set up using the SMB allows connecting different, commercial available power grid simulation and analysis tools. With these it is possible to model the physical environment of the controller in a very detailed way (Fig. 3). A simulation of the controller against different modelled power grids allows to challenge the implementation, find points for improvements and precisely measure its behaviour in multiple realistic application contexts. Within the project *DG DemoNet – Smart LV Grid*, PowerFactory from DIgSILENT is used for grid simulation. The alternative connection of SINCAL from Siemens takes place within the framework of a Ph.D. thesis at Vienna University of Technology. With the complete set up it is possible to simulate and emulate various scenarios considering different network topologies or states. The main utilization within the project is a technical assessment of different control approaches like described in [9]. First results of these simulations are discussed within the corresponding paper [5].

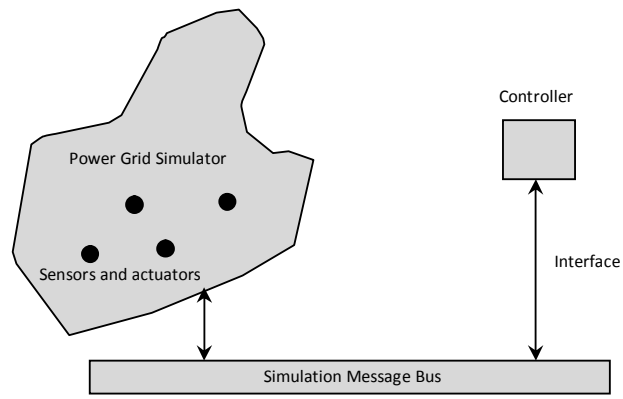

Fig. 4. Using a power grid simulator coupled to the controller under development, a more realistic environment model with the same interface can be provided.

D. Control Concepts with Co-Simulation

At a certain point in the development process it might make sense to consider the timing of message transfer in the real-world system. For this, a dedicated communication simulator such as OmNet++, NS3 etc. can be connected to the SMB (see Fig. 5). From here on, a co-simulation of multiple simulation domains is performed. The SMB supports the synchronisation between the individual simulators.

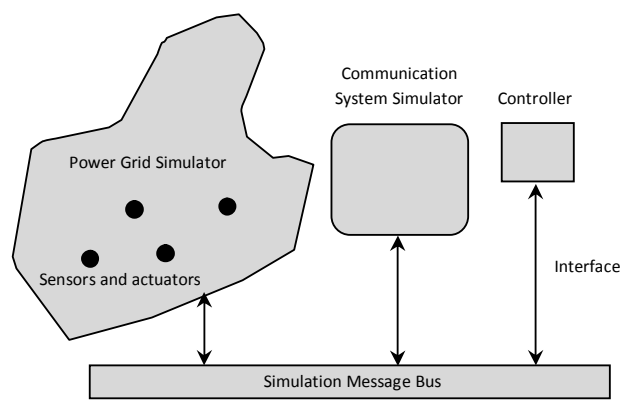

Fig. 5. The SMB allows to extend the environment simulation towards a co-simulation of e.g. power grid and communication network.

E. Control Concepts C-HIL Simulation

Once the control concepts are validated in simulation the identical algorithm can be transferred to the target hardware, in case of *DG DemoNet – Smart LV Grid* an industrial PC with

LINUX and a JAVA framework running on it. Similar to the simulations before, selected algorithms can be tested under the constraints of the real hardware in a Controller-Hardware in the Loop (C-HIL) simulation environment. In this step, the SMB strongly supports the seamless migration from the evaluation of a software-only controller implementation to the real hardware of the controller. Physical interfaces can be easily inserted into any of the TCP/IP-connections between SMB and the attached modules. If protocol translations are necessary, these can be realized within the message bus connectors by an additional translation proxy. Additionally it is also possible to connect other individual real-world components e.g. a PV inverter with distributed control functionality. In future it will be possible to test control functionalities of these components together with overlaying control systems in a HIL-Test-Laboratory to find out the optimal settings for component and system controller.

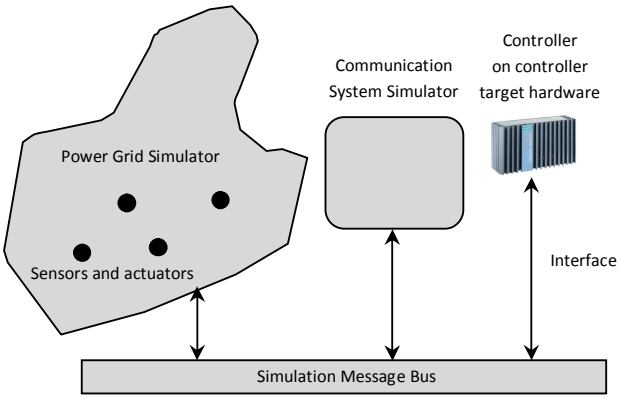

Fig. 6. Due to the realistic interface and modular structure of the SMB, the simulated controller can easily be extended by a real hardware component resulting in a controller-hardware-in-the-loop (C-HIL) test.

F. Control Concept Operation in the Field

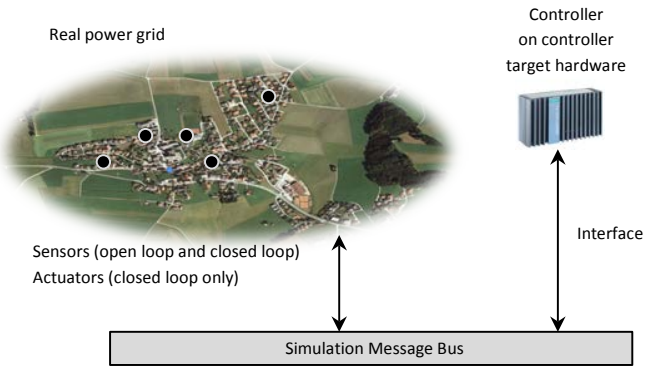

Fig. 7. Finally exchanging also the simulated environment with the real world, the SMB remains as an interface with configuration, logging and management capabilities of open and closed loop operation

After successful tests of the algorithms under the constraints of target system the controller hardware can be removed from C-HIL-Test-Laboratory and installed in e.g. the secondary substation. There, automation hardware will be connected to ensure the communication to all sensors and actuators in the field. In case of the Smart LV Grid project, the target hardware is the already mentioned industrial PC, the automation hardware is the data concentrator and the sensors are Smart Meters. The actuators are the tap changer in the secondary substation as well as PV inverters with integrated droop control functionality in the field. The field test operation is separated into two phases: In the first phase the controller is working in open loop. That is to say, the SLVG-C gets information about the actual grid status via Smart Meter values. The different control algorithms are using this information to generate the control values for selected actuators, e.g. tapping commands for OLTC or an update for characteristic curves for PV inverters. These commands are blocked by Supervisor and therefore not enabled for execution. To ensure a secure operation the controller has to pass a set of defined test cases for each control stage in open loop. Then there is nothing standing in the way for starting the closed loop phase.

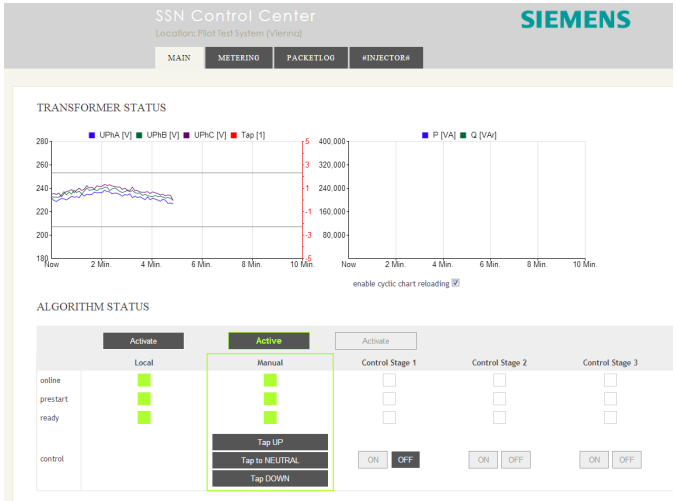

Fig. 8. Controller interface tab 1 showing general status view with bus bar voltage profile, active and reactive power chart and manual tap change options

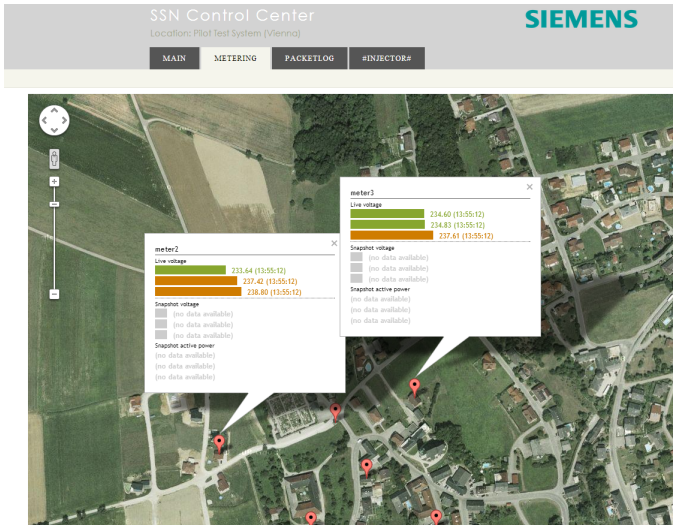

Fig. 9. Controller interface tab 2 showing a map of the field test region with OLTC and selected meters

To support the open as well as the closed loop phase a flexible web interface was integrated on SLVG-C. The first tab of the web interface offers a general SLVG-C status view (see figure 8) with bus bar voltage profile and active and reactive

power flow in the LV grid. Additionally there is a possibility to execute a manual tap change of OLTC. Figure 9 shows the second tab offering a map of field test region with OLTC and selected meter. For detailed analysis and debugging a filterable and sortable data logging of all values and status messages is integrated in the third tab (see figure 10). Last but not least the Injector tab (figure 11) can be used for testing of new functionalities or setting control values manually.

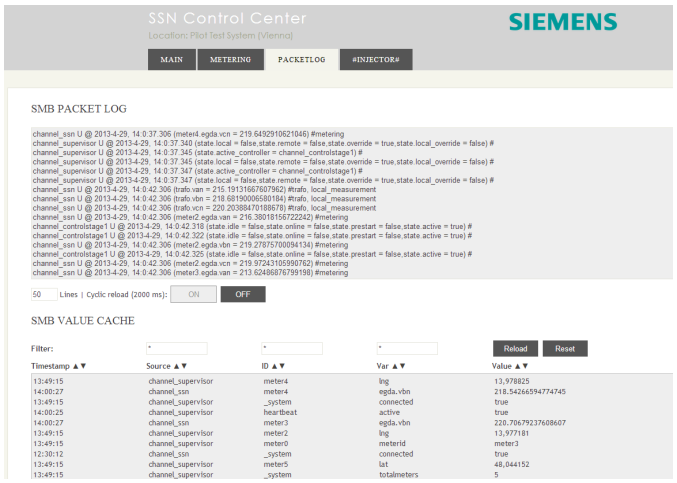

Fig. 10. Controller interface tab 3 showing a filterable and sortable data logging for detailed analysis and debugging

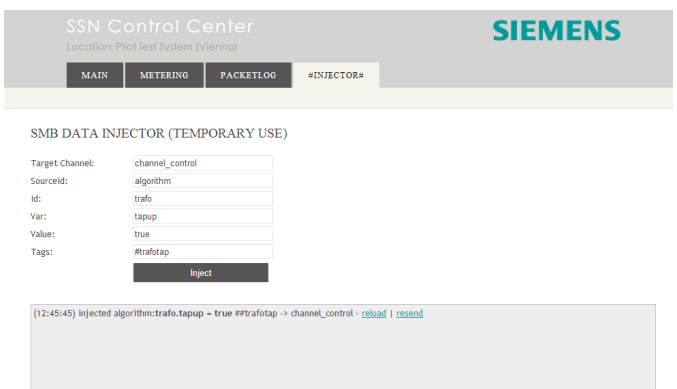

Fig. 11. Controller interface tab 4 showing an packet injection form for testing or manual data manipulation

G. Control Concepts Refactoring

Sophisticated logging and persistence tools built into the SMB allow for comprehensive validation and monitoring of live operation. Feedback from open-loop field tests and corresponding data can be used to refactor and improve control algorithms. The established development chain now allows for extremely quick turnaround of refactored algorithm to field deployment: the algorithm is developed, run through the test chain and deployed as-is in the field.

V. Results and Conclusion

With the introduction of the Simulation Message Bus (SMB) in the design, development and verification processes of control components for smart power grids, a rapid-prototyping methodology has been introduced. The methodology has successfully been applied in the *DG DemoNet – Smart LV Grid* project, where a voltage control unit for low voltage distribution grids is developed. The sensor values are coming from smart meters in the field. Actuators are the central on-load tap changer and distributed photovoltaic inverters in the field that feature on-line power factor adjustment (see also [5]). Experiences made in the above mentioned project have led to an improved routing configuration capabilities for the SMB. The more precise and close the simulation comes to the real world system, the more individual components have to be coupled and message paths to be configured. By using the SMB in the prototyping process, the developed controller algorithm stays the same during the whole development process. There is no need for porting the draft code to another platform or change of the interfaces to the outer world. This also allows an easy and fast refactoring process, since the tool set and overall set-up of the development environment does not have to be changed when rolling back in the development chain.

Acknowledgment

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