The German large scale demonstration project inside GRID4EU: Challenges of an autonomous Medium Voltage control system

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ABSTRACT

The German large scale demonstration project of the FP7 funded European project GRID4EU (1) (www.grid4eu.eu) addresses the development, implementation and field test of an autonomous grid control system in the Medium Voltage (MV) level.

The high share and still massively increasing amount of distributed generation, predominately wind and photovoltaic sets new challenges to the DSOs. In order to provide hosting capacity to integrate these resources huge investments in grid infrastructure are required. Grid operation and grid observation becomes more complex since power flows become less predictable. At present in Germany there are hardly any surveillance facilities or grid automation in place in MV networks.

The basic idea of the German demonstration [1-5] addresses an extension of the automation level of MV networks based on an autonomously acting and switching grid control system as an industrial solution for network operation.

INTRODUCTION

The following objectives are targeted:

- Integrating an increasing number of decentralized energy resources (DER) in the MV network and underlying Low Voltage (LV) networks
- Avoiding "classical" network expansion measures
- Achieving higher reliability, shorter recovery times after grid failures
- Avoiding unknown overloads and voltage violations
- Fulfilling the needs of surveillance and remote-control in MV networks
- Reducing network losses

This approach enables an autonomous interaction between the installed modules and their responsibility for a defined part of the MV network. Figure 1 shows the basic communication structure of the system:

The demonstration project is built up in the area of Reken, located in North Rhine-Westphalia, Germany. The considered grid is well selected since it shows already today a balance between installed generation power and maximum demand. A further increase in renewables to be connected is forecasted. The grid area of Reken consists of around 120 secondary substations where a total number of 18 substations is equipped with Switching (seven) and Measuring Modules (eleven).

This paper deals with the challenges of the system development as well as the experience of the field implementation. A key factor was the optimization process of a minimum number of modules and their location in the MV network structure. Switching Modules are placed at network nodes with a maximum number of possible and necessary switching operations due to the above mentioned objectives. Measuring Modules are positioned in the MV network to obtain a maximum monitoring with minimum equipment.
MODULE POSITIONING ALGORITHM

To evaluate the locations of switching modules two approaches have been applied separately [6]. A set of heuristic rules could be evaluated depending on the network topology and on the location of distributed generation. These rules give practical recommendations where to set separation points in the network for switching between different operational scenarios. The obtained separation point locations are modified and validated by load flow calculations.

The second approach, known from network planning, uses a heuristic optimization technique which starts with a completely meshed network structure and adjusts iterative separation points until the overall topology becomes radial.

Both methods lead to very similar results. By applying some operational restrictions for the location of switching modules the following set-up results are obtained:

- measurement inputs for current from each feeder
- measurement inputs for current and voltage on LV side
- battery
- power supply unit
- safety devices (fuses)
- current transducer in each feeder
- current transducer on LV side of the (secondary substation) transformer
- voltage taps to measure voltage level on LV side and providing the supply voltage

There are three different approaches used to deploy the seven switching modules:
- Switchboard next to existing substation
- Replacement of existing secondary substation
- Replacement of existing switchgear in walk-in substation

The first solution can be selected if size constraints, e.g. in a tower substation, do not allow the integration of the new switchgear into the existing substation but a complete replacement of the substation is not necessary. The second solution can be selected to replace either rather old substations (close or at the end of their lifetime) or if the new substation needs to be placed at a new location, e.g. due to updated grid planning. The third solution highly depends on the substance of the substation. Any other existing assets like e.g. the transformer or the LV distribution panel remain in operation.

SYSTEM ARCHITECTURE

The complete system structure and the core algorithms of the autonomous system were developed and tested by the TU Dortmund and ABB. The implementation of the communication infrastructure was accompanied by additional requirements of the information security management system (ISMS).

As already stated the core idea is to implement an autonomous system which is able to manage the grid without a high level SCADA system. To do that, two different approaches are possible:

- Centralized architecture, where the ‘intelligent’ functions are concentrated at the master module in the primary substation. Slave modules in the field perform only measurement acquisition and execution of control signals.
- Decentralized architecture, where all functions are implemented on the modules in the field and the system is working as an agent system.

Both methods have their advantages: A central system is much easier to implement and to maintain, but on the other hand a decentralized system has a significant higher...
robustness and flexibility. Here are still a lot of more pros and cons which were discussed, but beside this theoretical discussion, there are some other fundamental limiting factors in the context of the applied implementation.

One of those is the used hardware for all modules, which is a small RTU with limited performance and memory. The other important limitation is the fact, that standard PLC environment is used for the development of all functionality. The decision to use PLC has been made because of separating the development of all “Grid4EU”-functions from the RTU-firmware development. The advantage of this separation is the independency of both software packages. Therefore, they can be developed without influencing each other. But this advantage turns to a disadvantage in sense of performance. And finally only standard RTU protocols, like IEC 60870-5-104, can be used for the communication between the different modules. To mitigate these problems a hybrid solution is implemented. Calculations which are only based on information of the local secondary substations are implemented in a decentralized way in the slave modules, all others are performed in the master module.

The slave modules are responsible for acquisition and transmission of measurements, fault indications and breaker status signals. Local load forecast and local state machine functionalities are also outsourced to the slave modules. The local state machine is in charge of supervising the local limits for current and voltage. In case of a limit violation, this information is sent to the master module. The local forecast provides the most probable trend of the power flow for the next day.

The master module is implemented on the RTU placed in the primary substation Groß Reken. Its tasks are supervising the underlying medium-voltage power system, reacting to some particular operational situations and forwarding measurements, topology changes and its own action notifications to the superior SCADA-system.

The main function blocks of the master module are:

- State machine: determination of the overall system state (secure state ➔ faulty state)
- Optimisation: finding the loss-optimised target topology based on the actual situation/forecast of the slave modules and creating the switching program to reach this topology [7]
- Switching program management: Executing and supervising of the switching program

The Fault Detection, Isolation and Restauration (FDIR) can be part either of the master or the slave modules. To be more flexible the FDIR is implemented as a decentralized task. Our hybrid system architecture anticipates, beside the standard communication from master to slave, also peer-to-peer communication which enables neighboured slave modules to exchange data among each other. This dataflow is used to control the FDIR algorithm.

One essential part of the project is the communication between all modules. The direct implication of this is the need of a defined step by step procedure to ensure that the system is hardened against cyber-attacks. Figure 3 shows the steps which are taken. In the first step the protection requirements are determined, followed by a risk analysis and applying a standard procedure for IT security. After these steps it is clear what the risks are, how likely they are and what the potential damages are. With this defined procedure a security audit with all involved systems, like RTUs and routers, was performed, and finally followed by the implementation of the IT safety measures.

Fig. 3: ISMS process steps

SIMULATION RESULTS

Simulations are executed for two different purposes. The switching behavior is analyzed by simulation to get a first overview of the complete system before the implementation and operational phase. Second the impact of the installed switching module system is analyzed by means of typical key figures related to the system reliability.

Switching behavior

In order to prepare the control system for future field operation a laboratory test bed involving used automation hardware and a software network emulator has been implemented. A hardware-in-the-loop simulation allows testing and adapting the control system software which is running on the automation hardware. Here a simulation of the control algorithm for overload-driven switching action is exemplarily presented.

The algorithm runs centrally on the primary substation module and evaluates local states from all modules. When any voltage or current limit violation is detected, it is forwarded to the central module as a trigger for optimization routine. An optimal violation-clearing topology state is then suggested and a corresponding control actions scheme is applied.

In Fig. 4 the described situation is illustrated for the case of voltage violation. The voltage of one monitored

![Fig. 4: Voltage violation scenario](image-url)
substation crosses a 10.7 kV mark, which is defined as near-critical, and after exceeding a defined time the algorithm is activated. Finally, switching to another topology improves the voltage behavior and puts the system into a secure state.

![Time-dependent voltage variation](image1)

**Fig. 4: Time-dependent voltage variation of a critical grid node with and without the switching module system**

In the following, the single steps of the control system behavior are listed (numbers compare to Fig. 4):

0. Simulation begins  
1. Secure voltage state is left  
2. Control Algorithm is active  
3. Optimization process is started  
4. Optimization finishes, switching sequence is written, execution is activated  
5. Switching process is started  
6. Switching process finishes  
7. Simulation ends

The described simulation is carried out in real time. The switching process consists of one switch closing and one opening command. It is notable that the entire process from detecting a problem till its elimination (steps 1-6) takes about 5 minutes which is considered as an adequate reaction time. This time period includes the optimization runtime and the switching process, consisting of switching gear reaction times and idle times for successful switching notifications.

All in all, simulation results show a correct system behavior when reacting to overvoltages or overloads. The reaction time is appropriate regarding laboratory conditions – ideal communication between modules, smooth continuously changing measurements signals and correct switching gear operation. When testing the system’s behavior under field conditions these factors may require some software adoption. By demonstrating the overvoltage elimination test case the benefit of automated network topology reconfiguration is evident compared to conventional static operation without switching.

**Effects on reliability**

The positive impact of the switching module system was analyzed by the comparison of the typical reliability key numbers SAIDI and ASIDI with and without the system implementation. Table 1 gives an overview of these values:

<table>
<thead>
<tr>
<th>Situation</th>
<th>SAIDI in min/a</th>
<th>ASIDI in min/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current state</td>
<td>12.8</td>
<td>14.9</td>
</tr>
<tr>
<td>System applied</td>
<td>6.1</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 1: Reliability key numbers

Fig. 5 shows exemplarily the corresponding non-availability Q (product of power outage frequency and duration) of all MV network nodes for both cases:

![Non-availability Q](image2)

**Fig. 5: Non-availability Q of all MV network nodes**

It is obvious that the system implementation results in shorter outage times of the complete network. The limited number of used switching modules is sufficient to increase the reliability at all network nodes significantly.

**FIELD TEST IN 2015**

The operational implementation was divided into four phases of operational autonomy:

1. **Recording of measured values and signals**  
   => “no switching”

   In this first phase only measurements are recorded in order to get an insight view on the real situations and power flows in the network. Check and optimization of the components’ stability and their interaction constitutes to be the focus of this phase.

2. **Semi-automatic switching step 1**  
   => “switching via SCADA”

   In the second phase the optimization algorithms in the dispersed devices are tested for the first time. Reason for a topology change and target state of the switches are
transmitted to the central SCADA system. There the proposed changes are going to be analyzed by the control center staff. If the proposal is approved the corresponding switches are manually advised to execute the topology change. Besides the algorithms also the ICT infrastructure to operate the switches is going to be tested further.

3. Semi-automatic switching step 2
   => “switching via central RTU”

The third phase is comparable to the second one. Main difference is the higher level of autonomy of the system operation. The central RTU transmits proposed changes in the same way as in phase two to the SCADA. Now the control center staff only has to approve the proposal as a “final check”. Any further steps are processed automatically in the central and distributed RTUs. Thus respective signals and commands are going to be sent to the switches without further interaction with the control center.

4. Autonomous switching

Finally the phase of “autonomous switching” should be tested. No manual interaction nor approval from the control center is needed. The system works autonomously, i.e. it changes the network’s topology according to the actual grid conditions fully automated. Solely relevant information like alarms and the current network topology is going to be transmitted to the control center (SCADA).

CONCLUSION

The German Demo of the European project GRID4EU is focused on the basic idea of an autonomously acting and switching grid control system in the medium voltage level. In summary this paper gives an overview on the basic system architecture, the challenges of a respective field implementation and first experience of the operational phase which continues until the end of 2015. Additional simulations show the potential of this solution and will be completed with an economic analysis in 2015.

REFERENCES