Concept and Requirements of a Simulator for Substation Automation Systems

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Abstract—Increase of dispersed generation in medium-voltage-grids and lack of practical experience with new standards form dangerous impacts on current control- and protection functions that are part of substation automation systems. To overcome these problems a simulator proposed, that supports the development of new protection systems and provides practical training opportunities in terms of IEC 61850. Real secondary equipment forms a substation, while the subimposed process, the primary equipment of the substation and the ambient power system, is simulated with a real-time simulator. Amplifiers are coupled to the simulator and allow for the emulation of the secondary currents and voltages of instrument transformers at a maximum frequency of up to 20 kHz. Conclusively relevant fault scenarios including transients during earth faults can be simulated.

Index Terms—dispersed generation, IEC 61850, power system faults, power system harmonics, power system simulation, power system testing, protective relaying, training

I. INTRODUCTION

Safe, reliable and economic operation of power-systems relies on Substation-automation-systems (SAS), which coordinate protection and control functions inside substations and interface with superimposed telecontrol applications. Smart-grids must include operating consumers and dispersed energy resources (DER) in a coordinated manner with the SAS. Advances in information and communication technologies must be applied to put comprehensive smart-grid-technologies into practice.

The Institute of Power Systems and Power Economics at the Technische Universität Dortmund develops a substation simulator, which enables comprehensive emulation of the protection and control in electrical power systems. It combines the aspect of telecontrol with SAS down to the coordination of DER.

Section II of this paper studies the current state of technologies of SAS. It analyses the challenges, that protection systems are facing and recent developments that are driven by IT-technologies, which can contribute to the solution of the related problems. Section III presents the concept of a substation simulator, which helps to solve current problems by accelerating the adoption of new IT-technologies in power systems. Subsequently the main requirements of the simulator are developed on the base of future use-cases. Section IV describes the implementation of the simulator, which comprises a software model, simulation hardware and interfaces and the corresponding secondary equipment. The performance of the process simulation is evaluated by emulating an exemplary fault scenario. The article ends by a conclusion and outlook in Section V.

II. DRAWBACKS OF THE CURRENT STATE OF TECHNOLOGY AND CURRENT DEVELOPMENTS

A. Drawbacks of current Protection Systems

The increase of DER can lead to dangerous problems for the correct adjustment of power system protection. Current protection schemes have been parameterized according to short-circuit calculations, which do in general not consider the particular behavior of DER during faults. Varying short-circuit-power of e.g. wind power plants, which ranges from zero to values slightly higher than rated power, renders over-current based fault-detection useless. A current German grid code for DER therefore defines undervoltage tripping as the main means of protection [12]. This approach is safe, but lacks selectivity, because this method cannot detect the defective part at the bottom of the potential gradient. Distance- and differential-protection are effective countermeasures in this context, but less cost-effective than time-overcurrent protection, the preferred solution in medium-voltage-grids. New concepts for protection-schemes must be implemented as economic solutions that make use of safe data exchange between DER and SAS.

Another protection function, which must be reconsidered during the integration of DER, is auto-reclosing. It cannot interrupt self-healing faults, if the DER feeds the fault during auto-reclosing-cycles. As a solution the DER must coordinate its protection with the SAS, which implements auto-reclosing. Another impact on power system protection is caused by the increasing number of power electronics components. Wind power plants of the actual state of technology are either
entirely or at least partly coupled to the grid via inverters. The influence of the thereby caused harmonics on the protection system must be considered.

So far only technical issues have been addressed. However, a significant part of the malfunctions of protection-systems are not caused by equipment failure but appear to be human-made mistakes. The increase in functional density in current digital protective-relays renders configuration of these devices more complex. The state of technology in medium-voltage substations comprises the use of a single bay device per feeder, which executes several protection functions as well as the control of the bay from the station control level. Proper configuration demands a wide base of knowledge to properly accomplish the following steps to set an SAS in operation:

1. Coupling of the bay-devices to the process
2. Choice of the protection functions
3. Logical conjunction of control- and protection-functions
4. Setting of the protection parameters
5. Configuration of the coupling to the station-bus
6. Functional tests (secondary injection tests)

In common cases one person executes this whole chain using comprehensive software tools. Mistakes can be done, so that e.g. signals are not correctly communicated. These mistakes can remain unidentified until they cause severe malfunctions, because personal and time lack for sufficient testing.

With an increase of knowledge among the operational staff the amount of mistakes can be reduced. Comprehensive and realistic training facilities can be useful tools in this context. If nonetheless wrong settings have been applied advanced applications can remotely check, compare and eventually correct relay settings to eliminate a common cause for malfunctions.

B. Recent Advances

Optimizing the, if properly configured, well-performing local protection by for instance developing new algorithms is not the solution to overcome the challenges for protection systems in our days. New concepts, which make use of measured data from remote points in the network and coordination between DER and SAS can both significantly improve selectivity and provide further redundancy. Data from phasor measurement units (PMUs) can support the protection system. Concepts exist, as given in [8], which must be implemented in practical applications.

The key for advanced comprehensive communication in the power system is vendor-independent communication. Currently available for this purpose is IEC61850. Although originally created to be used within substations its standardized object-model makes it uniquely applicable among the whole power system ranging from telecontrol down to control of DERs. Practical experience, realistic testing facilities and education opportunities are required to accelerate the adoption of this technology.

The following section III develops a concept for a substation simulator, which is meant to accelerate the adoption of current advances to cope with the drawbacks of the current state of technology.

III. SPECIFICATIONS OF THE SUBSTATION SIMULATOR

A. Concept of the Substation Simulator

A substation simulator can serve as both a test bed for new devices and as a training facility (Fig. 1). It features closed-loop-testing and reflects both control- and protection functions within the substation and interaction with the telecontrol-system. A process image, which comprises for instance line-currents, bus-bar-voltages and status of circuit-breakers, is generated by a process-simulator and communicated to real secondary equipment.

Commercially available secondary equipment of the latest state of technology is included, which avoids the development of e.g. IEC61850-protocol-stacks as described for instance in [9] or the emulation of protective relays in software like in [10]. The use of real devices creates a realistic surrounding, which includes protection functions and communication protocols.

![Fig. 1. Basic concept of the substation simulator](image)

The subimposed process-simulator allows for closed-loop-testing of the control and protection equipment. The simulator must calculate the model faster than real time and provide the process image through a suitable interface. The control- and protection layer reacts to simulated events, e.g. short-circuits, with control commands, which are fed-back into the grid-model. A counter-reaction of the systems is evoked, thus closed-loop testing is achieved. Compared to open-loop testing, which is focused on verifying parameters and device-functionality, closed-loop-testing is able to analyze the influence of a whole protection-system on the dynamics of the simulated power system.
B. Requirements for the process simulator

A commercially available solution for the process simulator must be obtained, which satisfies the following criteria:

- Flexibility
- Grid-Size
- Applicability
- Frequency requirements for the process-interface

The amount of efforts that adaptation to the simulation model causes, defines the aspect flexibility. Modular software models, which are implemented with common software tools, offer the best performance.

The size of the grid, that the simulator is able to execute, must fit its application. The performance of the process image is reduced with increasing grid-size, if computing performance remains constant. To avoid the use of networks with high performance requirements and possible difficulties with splitting and synchronizing dispersed models, the model should be executed on one single computer.

Applicability is influenced by the data-interfaces of the simulator. If grid-models from other popular software tools can be imported, the adoption of a simulator will be eased. Comprehensive libraries with common power-system-components, e.g. transformers and lines, contribute to this aspect.

Requirements for the process interface are basically characterized by the minimum step size, at which the simulator is able to generate the process image. According to the Nyquist criterion the related step size must be at least two times shorter than the inverse of the maximum required frequency. The latter depends on the subject application and is a decisive criterion to both computing performance and the bandwidth of the process interface. Relevant standards and the current state of technology for protective devices are investigated in the following paragraphs to acquire the related requirements, which are illustrated in Fig. 2.

Exemplary commercially available protective relay applies a low-pass filter to the input signals with a cut-off frequency of about 2.2 kHz [3]. Another competitor applies a sampling rate of 3.2 kHz, so that conditional to the Nyquist criterion the maximum frequency, which can be analyzed is below 1.6 kHz [5]. But also significantly lower sampling rates of 800 Hz are in use [4]. As an exception to the rule transient earth fault-detection, which is applied in compensated and isolated grids, can require input signals up to 12 kHz [7].

Standards for analysis of harmonics provide another reference point. For evaluation of power quality in the context of dispersed generation IEC 61000-4-30 defines measuring up to the 50th harmonics, which corresponds to 2.5 kHz in 50 Hz grids [13]. According to EN 501060 analysis of harmonics up to 1.25 kHz are sufficient [14].

Another source for requirements is IEC61850. It describes merging units that connect bay devices to signal acquisition in the field by use of sampled values on a digital process bus. In this context secondary values of the instrument transformers should be sampled at a rate of either 4 kHz or 12.8 kHz, which can process frequencies of up to 2 kHz or 6.4 kHz [6].

In the following section IV the substation simulator is implemented in respect of the given requirements.

IV. IMPLEMENTATION OF THE SUBSTATION SIMULATOR

A. Simulation Model

The High-voltage-level (HV-level) has not been selected as a suitable field of application for the substation simulator. Due to the relatively weak economic restrictions HV substations do not significantly demand new technologies. Protective devices are sophisticated and approved technologies and the high requirements for reliability inhibit the adoption of innovations. Wind farms from about 20 MW on typically feed in the HV grid. Equipping them with distance-protection is less restricted by economic limits.

Protection and control in low-voltage-grids (LV-grids) contrast the situation in HV-grids. As LV-grids form a big part of the power system and as black-outs are in general accepted, economic reasons restrict the use of sophisticated protection functions. Fuses are the main means of protection and safe communication channels practically do not exist. Therefore LV grids do not offer potential for new protective functions in near future.

The simulation model focuses on the medium-voltage-level (MV-level), because solutions for economic and effective control and protection devices are required. At the same time new technologies are likely to be accepted. The model comprises a substation, which connects an HV-grid to an MV-grid with consumers and DER. The center of the simulation consists of the model of an MV-substation (Fig. 3). To reduce implementation efforts and achieve a good usability, the structure of the substation is simplified compared to the reality and its size is reduced to four bays.

![Fig. 2. Requirements for process simulation in respect of typical applications](image-url)
A transformer bay connects the busbar to the HV-grid. Depending on its total capacitance, the MV-grid is isolated or compensated with the related reactor connected to the transformer’s star point. Low-impedance grounding can be activated during a short time to trip over-current-protection in case of earth faults. Current-differential protection of the transformer requires the use of two current transformers.

Two feeder bays of the same structure couple the ambient MV-grid to the substation. Each bay can be controlled via one circuit-breaker and two disconnector switches. One current transformer for each bay and a common voltage transformer in a measurement bay provide an interface to the secondary equipment.

While the basic structure of the MV substation cannot be changed due to the process-coupling to the secondary equipment, the ambient HV- and MV-grid can be adapted by via software. The HV-grid can for instance also comprise HVDC-components. The MV grid models both consumers and DERs, like single wind power plants and cogeneration units of more than 200 kVA rated power.

B. Simulator and Process Interface

The model of the process is executed on a real-time-digital-simulator, which is composed of a standard PC and hardware for the conversion of binary and analogue signals. The simulation model is implemented in Matlab/Simulink® on a Host-PC. Then the model is compiled and loaded on the real time digital simulator, the target PC. This simulator has been chosen for the following reasons:

- Commercial availability
- Use of standard-PC-platform
- Use of proven development tools (Matlab/Simulink® with SimPowerSystems®)
- Proven for simulating wind power-plants and HVDC-devices

As the real-time-simulator uses low-level analogue signals additional amplifiers adapt to the common secondary values of instrument transformers (1A, 100V). To satisfy the requirements for simulating earth faults at reasonable costs, both commercial off-the-shelf amplifiers with a bandwidth up to 6 kHz are used as well as specially designed amplifiers, which can operate up to 20 kHz. Depending on the application, the right analogue interface must be used.

Although low-level signals from Rogowski-coils and also digital process-bus-interfaces according to IEC 61850-9-2 exist, they are not considered yet. They namely either lack commercial availability or they are implemented as vendor-dependent solutions [15]. Extending the simulator with a process bus interface, as it has been implemented in [11], can be a future expansion.

C. Secondary Equipment of the Substation

Protection and control at the substation comprises real substation equipment of the actual state of technology (Fig. 3). Instead of a conventional remote-terminal-unit a station computer enables automation functions and a human-machine-interface. An IEC 61850 station bus is implemented.

A PMU measures the bus-bar-voltage in a time-synchronized manner. An additional “device under test”, for instance a second PMU, can virtually be connected to any other process value in the software model. The PMU can then be physically linked to the SAS, so that e.g. the phase angle between the substation and the DER terminal voltage can be acquired and used by new protection applications. This application takes both execution time for signal and data processing as well as communication time delay into account.

Protection and Control of each feeder is carried-out by one multifunctional bay device. The transformer-bay is additionally equipped with a separated differential-protection. This setup is typical for MV substations and saves efforts for the implementation, because the number of devices remains fairly low. Multifunctional bay devices also offer flexible functionality, so that the assignment of protective and control functions can be done almost independently of the chosen devices. These functions are assigned by using engineering tools in respect of IEC61850-6 [16].

D. Case Study

The evaluation focuses on the emulation of one feeder with automatic low impedance grounding of the neutral during an earthfault (Fig. 4). The model is implemented using Matlab/Simulink® and the toolbox SimPowerSystems®. An MV-grid comprises power transformer and the related HV-grid that are connected to the feeder. Inside the bay voltage- and current-transformers do not restrict the signals due to saturation effects and angle-inaccuracies when transmitting.
them first to the I/Os of the process simulator. Behind the I/Os amplifiers adapt current and voltage signals to common instrument transformer levels, before they are acquired by a bay device which applies a definite-time over current protection with one stage to the corresponding circuit breaker CB0. A load is connected to the feeder through an MV-cable.

![Fig. 4. Simplified circuit diagram of the case study](image)

The attributes of the components have been parameterized according to typical positive- and negative sequence values. Zero-sequence values, which are in practice significantly influenced by uncertain parameters, have been estimated according to [2]. Table I in the appendix summarizes the specifications of the model in detail.

To verify the proper function of the process emulation, relevant process values are acquired and analyzed during the execution of the scenario. The measurements have been exported from the simulator and represent primary values. The scenario starts with normal operation at a load current on phase a (Iₐ, rms) of about 300 A (Fig. 5). After 2 seconds a persisting earth fault occurs on phase a, so that its line-to-ground voltage (Vₐ, rms) drops to almost zero. Due to the isolated neutral and the relatively low total capacitance of the MV-grid and cable the subject current does not significantly change. At this moment transients occur especially on the voltage of the non-faulted phase b, while Vₑₐ rises by factor √3 to the corresponding line-to-line value (Fig. 6). The protection of the feeder is supposed not to interfere at this moment. According to the chosen protection concept low impedance grounding of the MV-grid’s neutral is activated after 5 s. Subsequently Iₑₐ peaks to a short circuit value of about 750 A, which is supposed to pick-up the over current protection of the subject feeder. Conclusively the process emulation has behaved in the expected manner and is therefore approved for testing of bay devices with the corresponding time over current protection functions.

Currently a bay device is operated in closed-loop with the simulator. First tests have revealed the proper function of the process interface. However, technical problems have been delaying the tests and did not allow publishing results for this paper in time.

![Fig. 5. RMS-Values of relevant voltages and currents during case study without interaction of the bay device](image)

![Fig. 6. Current of phase a and voltage on phase b during occurrence of an earthfault on phase a](image)

V. CONCLUSION AND OUTLOOK

A concept for a substation simulator has been developed, that allows for comprehensive emulation of power-system protection and control. A hybrid approach has been chosen, which consists of the simulation of a medium-voltage substation and its related power system on a real time digital simulator that generates a process image to secondary equipment. For modeling faults and harmonics the instrument transformer signal must be emulated in a range between 2 kHz and 12 kHz. Care must be taken, that both the step size of the simulated model fits this requirement and that additional amplifiers do not become an undesired restriction.

During a case study the simulator concept has been evaluated. It was proven that it is possible to implement fault scenarios in a time efficient manner.

As next steps the functions of the substation will be engineered according to IEC61850-6. Afterwards new devices and applications can be tested and training courses can be carried out on the base of the substation simulator.
VI. APPENDIX

TABLE I
SPECIFICATIONS OF THE MODEL FOR THE CASE STUDY

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation step size</td>
<td>50 µs</td>
</tr>
<tr>
<td>MV-grid</td>
<td></td>
</tr>
<tr>
<td>Short-circuit power</td>
<td>$S = 500 \text{ MVA}$</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>$U_r = 10 \text{kV}$</td>
</tr>
<tr>
<td>X-R ratio</td>
<td>X/R = 10</td>
</tr>
<tr>
<td>Grounding</td>
<td>Isolated star point with reversible grounding resistor</td>
</tr>
<tr>
<td>Grounding resistor</td>
<td>$R_g = 10 \Omega$</td>
</tr>
<tr>
<td>Voltage transformer</td>
<td>10 kV / 100 V, ideal behavior</td>
</tr>
<tr>
<td>Current transformer</td>
<td>400 A / 1 A, ideal behavior</td>
</tr>
<tr>
<td>Cable</td>
<td></td>
</tr>
<tr>
<td>Type, Length</td>
<td>NA2XS2Y 3x240mm², l=10 km</td>
</tr>
<tr>
<td>Positive and Negative Sequence (per unit length)</td>
<td>$R' = R_n = 125 \text{ mS} / \text{km}$, $L' = L_n = 0.34 \text{ mH} / \text{km}$</td>
</tr>
<tr>
<td>Zero-sequence (per unit length)</td>
<td>$C' = C_n = 456 \text{ nF} / \text{km}$</td>
</tr>
<tr>
<td>Load</td>
<td>$P=5 \text{ MW}, Q=0.5 \text{ MVar}$</td>
</tr>
<tr>
<td>Fault</td>
<td>Earthfault on phase a</td>
</tr>
<tr>
<td>Location</td>
<td>5 km from the feeder</td>
</tr>
<tr>
<td>Fault impedance</td>
<td>$Z_f = 0 \Omega$</td>
</tr>
</tbody>
</table>

VII. REFERENCES

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VIII. BIOGRAPHIES

Michael Kleemann received his diploma degree in electrical engineering in 2007 from the Technische Universität Dortmund, Germany. After graduating he started working as a research associate at the Institute of Power Systems and Power Economics of this university. Testing of protection systems and enhancing power-system control and protection systems by use of new IT technologies form his main research interests.

Kay J. Görner received his diploma degree in 2007 at Technische Universität Dortmund, Germany. Since then he is a staff member of the Institute of Energy Systems and Power Economics at the Technische Universität Dortmund. His main research interests are investigation and development of power system applications for the integration of Wide Area Monitoring Systems as well as improvement of measurement-algorithms in Phasor Measurement Units.

Christian Rehtanz (SM’06) was born in Germany in 1968. He received the Diploma and Ph.D. degrees in electrical engineering from the University of Dortmund, Germany, in 1994 and 1997, respectively. In 2000, he was with ABB Corporate Research, Switzerland, where he became Head of Technology in 2003 for the global ABB business area of power systems. In 2005, he became Director of ABB Corporate Research in China. Since 2007, he has been Professor and Head of the Institute for Power Systems and Power Economics at the TU Dortmund University. His research activities include new technologies for transmission and distribution.