A Real time development platform for next generation of power systems control functions

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Abstract: A real time development platform for simulation studies of control and operation of next generation of power systems control functions is introduced. The platform covers all aspects of the challenges of future power systems requirements related to operation and control. In this paper the requirements of a simulation platform will be formulated. A laboratory setup with special attention to the utilization of real time simulation equipment and some typical reference applications will be described.

Keywords: Real Time Simulation, SCADA, Control System, Power Quality Monitoring, Power System Control & Operation, Information and Communication Technologies, Protocols, IEC61850, IEC60870-5-104, DNP3

I. INTRODUCTION

It is well known that the modern power system is a large sophisticated technological entity which developed over decades. It has been designed in a time, when electricity was a minor energy source, not available for the entire society, but for special applications. Today electrical energy covers a substantial part of the total energy consumption. Initially the electricity supply industry operates in a demand following way. This approach is appropriate as long as sufficient controllable generation capacity is available to meet the demand fluctuations. Until the 1990s nearly 100% of the electricity came from central generation units. The power was fed into the high voltage transmission network and then distributed through medium and low voltage networks to the end customers. In fact, power systems were organized in a hierarchical way [1], [2].

The liberalization of the power market enabled access of small power units to the grid without discrimination. With unbundling the network and power generation control separated into different independent entities not keen to exchange business relevant information with respect to their operation. In particular in Germany, policies have been established to increase the amount of renewable or combined heat and power and to make the grid operators responsible for power quality or loss of supply. These are further forced by problems with respect to global warming, scarcity of fossil resources, efficiency and product quality. Real time pricing, advanced control of power flow, demand side management, non deterministic infeed, market driven operation between costs, risk and liability make more difficult the electric power network control. [1]-[4]

Key to these new requirements and phenomena of the power system is the real time data provision and communication between the power system control and operation framework. Real time processing means that a system has fixed operation deadlines from event to system response. A system is working in hard real time, if its operation depends on both, the logic correctness and its performance time. Soft real time tolerates delay but operates with reduced service quality. Fast Power system monitoring and regulation are hard real time operations, because their delay can cause power systems dynamic stability problems or failures in power system operation.

All forecasts foresee that the utilization of the energy carrier electricity will increase. For example hybrid or full electric vehicles need to be charged. They will be mainly connected to the low voltage distribution network. Due to the high load current and non-deterministic charging state it is necessary to control all the connected energy storages by a central station with respect to the network resources and the particular needs of the customers.

On the generation side the amount of photovoltaic schemes in the low and medium voltage networks is increasing due to governmental subsidies and developing technologies with growing efficiency factor, while wind power is changing from a decentralized energy suppliers with mainly random behavior to centralized ones with more deterministic behavior, due to changing from an onshore to an offshore technology [1], [2].

From a technological perspective all these developments will impact the network operation and the development of products for end customer development. The load characteristic may change towards a capability to store electricity. With an increased amount of fluctuating energy infeed the ability of a centralized frequency control decreases. Power electronic based grid interconnections might have a negative impact on power quality but offer reactive power control capabilities that must be properly used. In addition the power will not only flow from the transmission network to the distribution network. Power flow between different low voltage networks via the medium voltage level can occur as well [5]-[11].

New methods and system operation technologies have been developed. Based on the theory of “Microgrids” and “Intelligent Grids” several test facilities have been installed to design operating and control strategies. The information and communication technology has been identified as a key technology for all these new application cases. This results from an increased demand of monitoring and control.

Some technologies for real time control, as Wide Area Monitoring Systems (WAMS) and Wide Area Control Systems (WACS), have been introduced some years ago. They are based on the commercially available Phasor Measurement Units (PMU). With PMU’s the power system can be monitored in real time. The magnitude and angle of the bus voltages and line currents can be measured almost with no time delay as operated by the conventional state estimation. In combination with a suitable communication backbone the power system can be monitored with a response time less than one minute [12]-[21]. However, this technology is most suitable for wide area monitoring and control applications. These systems are hard real time systems.
In a conventional hierarchical power system the medium voltage grid has been designed for power distribution and to be fed from higher voltage levels, i.e. the transmission grid. The distribution grid has been designed to be passive without dedicated network control instance or large amount of measuring devices. The microgrid concept becomes necessary if small generation units are interconnected to the low voltage distribution system. Microgrids can be connected to the main power network. It can be operated islanded in a coordinated way. Microgrids and the transmission grid will be fully monitored in different timescales, due to their special requirements (see Figure 1 and 2). Historically, information and communication technologies (i.e. automation technologies) have not been installed in medium voltage distribution networks to vast amount. But in the light of the new operational objectives it becomes even more important since typical transmission tasks have to be fulfilled in the future.

Power system real time simulations are generally used in conjunction with external equipment, mostly built up as hardware in the loop application. Hardware in the loop simulations can be used for the design and evaluation of FACTS control and operation (FACTS, Flexible AC Transmission System). Another approach is to apply new mathematical models in order to speed up the entire simulation run. Real time simulations are used for highly complex analysis of the impact of power system devices (transformers, rotating machines, etc.). All these simulations focus on dedicated in-depth analysis of control loops with respect to their impact on the connected power network [22]-[39].

With respect to the above mentioned power system developments and the corresponding improvements in system simulation it is of utmost importance to include the underlying information and communication system (operation framework) into network simulations. The influence of the operation framework on power system security and stability will become decisive, if the amount of grid control increases. Today’s concern regarding safety and security of communication network is based control loops in power systems. Quality of service of IP (Internet Protocol) based control (delay, bandwidth, availability and so on) has not yet been investigated to a great extent because it is inherently assumed that this system is working fine.

Information and communication technologies (ICT) are normally neglected when it comes to power system operation analysis.

![Figure 1: Illustration of the expected development of the observability of power network (red parts are observed) (HV - high voltage, MV - mid voltage, LV - low voltage)](image)

In order to analyze and improve the ICT system of power systems the authors have developed a dedicated research platform that allows for various kinds of research with respect to ICT and power system control and operation. This platform covers all time phenomena of power system dynamics and is capable of simulating various kinds of network configurations and corresponding communication systems in real time. The proposed approach also allows for decoupled simulations for standalone power systems and/or communication systems. This paper outlines the basic requirements regarding such a platform. A comprehensive description of the architecture will be presented. After a general discussion of the laboratory setup example applications will be given.

II. REQUIREMENTS

Power System Simulator

The power system simulator has to match the following requirements: As standard for power system analysis the simulation has to be capable of subtransient and transient phenomena. Power electronic devices including harmonic analysis are necessary for a laboratory setup of an operation & control systems of grids including microgrid components and ICT systems. In this field a laboratory platform should allow for investigations of all phenomena that might dominate the operation of these networks. The environment should serve as test bed for higher optimization and decision functions for distribution grids including stability phenomena, grid islanding and power quality issues. The interest of large system analysis covers load flow analysis, integration of “renewable” and demand side management of loads or energy storages like hybrid or electric vehicles or domestic appliances with discontinuous load characteristic. In particular in the latter application area ICT becomes decisive for the simulation of multiple small load modifications in large systems. The entire system should allow for closed loop simulations including real ICT in order to study the impact of the entire secondary system on power system behavior.

Communication System Simulation

Due to the growing impact of communication systems the following requirements have to be met:

1) Use of standard protocols for communication,
2) IEC61850 support,
3) DNPv3 or IEC61850-5-104 support,
4) Support of ICCP,
5) Simulation of different communication channels (DSL, UMTS, Ethernet, etc.) for analyzing the impact of communication quality parameters to the primary process.

If standard protocols are applied, any commercially available equipment can be integrated for special scenario simulation. Most modern protection devices support communication via IEC 61850. Today, the standard for distributed measurement values, status information and operation between substation automation and network control systems is based on TCP/IP via DNPv3 or IEC61850-5-104 (Figure 3).

TCP/IP has become the “de facto standard” for computer communication in today’s networks. It allows for the use of standard components to build up a communication layer. The TCP/IP stack is available for the most communication systems and can be embedded into other protocols.

A change of the technology in layer 1 and 2, e.g. from Ethernet to wireless or UMTS only affects the TCP/IP support. Differences are expected in using a variety of communication channels (Layer 1 and 2). Those could be bandwidth, delay or package loss. Integration into the entire simulation framework allows for investigations of the impact of the communication system on the operational objectives of the power system.

**Control System Simulation**

Due to the high amount of information processing systems the following requirements have to match:

6) Real Network Control System (SCADA),
7) Real Substation Automation System.

For a comprehensive laboratory environment a fully integrated SCADA system is essential for real time operation and control of the simulated power systems.

With a closed-loop-simulation capability real-time modules could be tested and adapted to the process requirements during research activities (Figure 4). Table 1 gives an overview of the simulation requirements:

**Table 1:** Overview of Simulation Requirements

<table>
<thead>
<tr>
<th>Simulation Module</th>
<th>Requirements (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power System</td>
<td>- Transients and subtransients (R1)</td>
</tr>
<tr>
<td></td>
<td>- Harmonics (R2)</td>
</tr>
<tr>
<td></td>
<td>- Power electronics (R3)</td>
</tr>
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<td></td>
<td>- Large power systems (R4)</td>
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<tr>
<td></td>
<td>- Closed loop control &amp; protection (R5)</td>
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<tr>
<td>Communication System</td>
<td>- Standard communication protocols (R6)</td>
</tr>
<tr>
<td></td>
<td>- IEC61850 support (R7)</td>
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<td></td>
<td>- DNPv3 or IEC61850-5-104 support (R8)</td>
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<tr>
<td></td>
<td>- Support of ICCP (R9)</td>
</tr>
<tr>
<td></td>
<td>- Simulation communication channels (R10)</td>
</tr>
<tr>
<td>Control System</td>
<td>- Real Network Control System (R11)</td>
</tr>
<tr>
<td></td>
<td>- Real Substation Automation System (R12)</td>
</tr>
</tbody>
</table>

**Figure 4:** Generic function structure of power system control including the ICT systems

### III. LABORATORY SETUP

Due to the complexity of power system simulation and the need to cover most of the phenomena it is necessary to use specialized simulation cores with dedicated algorithms depending on the simulation requirements. The basic approach presented here is a hierarchical complex hybrid simulator. This simulator comprises six different components (Figure 5).
Physical Network Model

With the “physical network model” in-depth power system simulations can be provided. It is equipped with physical switches, approximate 900 km of line equivalents built from concentrated elements, and other physical equipment. This simulator can be considered as an analogue model of an electric power system. Advantages are the real time behavior and the absence of numerical model approximations. Due to the high complexity and degree of real hardware utilization this is limited in size and topology. It can be utilized for simulation of substations and sub-transient phenomena or secondary equipment hardware testing.

Digital Hardware Simulator

More flexible transient and sub-transient simulations are feasible by using a Real Time Digital Simulator (RTDS). In the proposed laboratory setup a simulator from RTDS Technologies Ltd. has been installed [38]. Here, the entire system is modeled by means of software modules. This gives more flexibility in size and topology. The simulator is specified and designed to have maximum computing and communication capability. Real time means a power system simulation resolution up to 50 µs, depending on the model complexity. The communication frontend supports IEC 61850 and DNP3. This allows using the simulator as a standalone process simulation either for substation automation systems, utilizing IEC61850, or bypassing this part of the control system, utilizing DNP3 as a direct communication to the network control center. The simulator also allows direct measurement for connection of monitoring devices for protection, power quality or real time monitoring. The RTDS system meets requirements R1 to R8.

Software Simulator

The larger the system under investigation the “simpler” the model needs to be. Due to limited computing power this particularly applies to real time investigations. Both, the “Dynamic Network Model” and the RTDS, define the limit of power system representation with respect to system size. Since the available RTDS system has been designed to have three racks, large power systems with more than three times 54 nodes needs to be simulated by software modules based on Matlab/Simulink and open source toolboxes which are used for loadflow calculations and midterm dynamics. With a special software setup of a RTU (simRTU) the software modules communicate with the SCADA system. SimRTU is a Java based implementation of the IEC60870-5-104 protocol for Matlab/Simulink. In the same way RTDS and SCADA form a closed-loop-simulation, the use of simRTU and Matlab based simulation on standard PC hardware represents a hardware in the loop application. This system meets requirements R4, R5, R6 and R8.

Network Control Center

The network control center is based on standard hardware and software for system operation purposes. The system consists of redundant server hardware, two operator workstations with the ability to use world map projection of the network situation of the operator desktops (Figure 6). The design of the room has been adopted from real network control centers for small and medium size networks. With respect to real world requirements this layout is fundamental for ongoing research of psychological aspects in stressed situations of network operators.

ICT Network Simulator

The information and communication system (CS) network simulator is used for the modification of variables in the communication layer between two connection points. All IP packages are routed through this system. Inside the communication channel values are defined, e.g. package loss or delay. The utilized system is the Wide Area Network Simulator (WANEM) [36].

IV. REFERENCE NETWORKS

SCADA Control System

To use full functionality of SCADA and network control systems, e.g. fault detection, automatic fault location, manual or automatic trouble shooting or reporting), a process simulation in real time with bidirectional communication of measurement and control values based on standard protocols is needed. The setup of the simulation architecture is shown in figure 7.

Figure 6: The network control center

Figure 7: Hardware in the loop simulation setup

The RTDS system simulates a sample power system in real time. Measurement and control values are transmitted utilizing DNP3 as communication protocol. A simple earth ground fault detection
system is modeled (Figure 8). If an earth fault is detected the SCA-DA system receives this information. In the following either the operator or the network control system should analyze where the ground fault is located and isolate the network of concern.

Figure 8: Reference simulation network for ground fault detection

Real Time Monitoring System

For real time monitoring purposes a hard real time process simulation is needed. Three phase instantaneous value measurements of a continuously operating network are essential for PMU based applications like Wide Area Measurement Systems (WAMS), Wide Area Protection Systems (WAPS) or Wide Area Control Systems (WACS). Due to the focus on the evolution of distribution networks one needs to develop a reference network for real time simulation with a high density of dispersed and regenerative generation. Figure 9 depicts a benchmark network that has been developed in the light of the focus described above. This network is simulated on a three rack RTDS system with a real time operation of 150µs.

Figure 9: Reference simulation network for real time monitoring

Rack 1 simulates a 110 kV circuit fed by a slack node. The circuit is modeled as a closed ring, stretched over the other two racks. In both respective racks a distribution system with a high density of dispersed generation is modeled. The system in rack one represents a 10 kV urban area shown in figure 10, rack two a 20-kV rural area. Both systems are modeled as an open ring with eight busses. Four induction machines represent a high amount of combined heat and power units, installed in urban areas. At both lines photovoltaic plants are installed. The loads are modeled as combined static voltage dependent and dynamic voltage independent loads. In addition at every line two induction machines, modeled as motor load, are installed. Each model represents an equivalent of the dynamic behavior of numerous infeed.

This network is designed to simulate transients and subtransients in real time for equipment testing also in the area of wide area monitoring or control systems as well as power quality monitoring.

On the one hand the proposed system setup, in connection with the real-time simulator, makes it possible to analyze power quality in medium voltage networks with a high percentage of dispersed generation. On the other hand, the system is able to serve as a test bed for research dedicated to future network monitoring systems as well as network control. In the proposed setup the power system simulation is done on RTDS hardware with a real time measurement system, see figure 11.

Figure 10: Subnetwork 10-kV

The real time target pc runs algorithms for power quality monitoring purposes, e.g. THD or harmonic content calculation. If an event is detected, the system records time series of monitored voltages and currents for post-event analysis.

Figure 11: Power quality monitoring system
V. APPLICATION STUDIES

MV Distribution Grid with high amount of dispersed Generation and Performance Test

The reference simulation network for real time monitoring (Figure 9 and 10) has been simulated with special interest in power systems stability of networks with a high density of dispersed generation. The major objective of this study was to test the capabilities of the real time simulation environment.

The example shows a step response of the 10 kV distribution network after remote switching of a photo voltaic (PV) generator. It will be used for further closed loop simulations with the SCADA system for control algorithm development.

Event based Power Quality Monitoring

This application has been defined in order to provide a comprehensive evaluation platform for event based power quality monitoring at the point of common coupling (PCC). The idea behind this new concept is to monitor power quality events based on negotiated emissions from both perspectives: network operator and customer. Here it is proposed to monitor the events based on the voltage magnitude at the PCC as described in the following: The negotiated voltage at the PCC is defined as

$$u_c(t) = \hat{U}_c \sin(\omega t)$$

(1)

All deviations from this voltage have to be classified with respect to “allowed” or “not allowed”. The deviations will be detected by events. Each event qualitatively describes a violation of a negotiated quality band. With respect to the different time ranges where voltage band violations could occur, it is proposed to define the voltage band based on instantaneous and RMS values depending on the time range of disturbances (threshold is $T_0$). The sliding RMS calculation will be done according to:

$$u_{RMS,x}(t) = \frac{1}{T_0} \int_{t-T_0}^{t} u^2(x) \, dx$$

(2)

Figure 15 and 16 are depicting an example of poor quality voltages at PCCs in different representations.

Based on a quality definition as described in [41] a quality event will be issued if a predefined threshold will be surpassed. The event will be registered with respect to importance and duration. The threshold definition is based on a quality band approach and needs to be defined in a load specific and network specific way.
With this approach an objective detection and evaluation of power quality events can be realized. In Figure 17 some examples of power quality events are given:

- 18% Dip for 100 ms (allowed)
- 50% Dip for 700 ms (threshold violation)
- Spike, 1.85 * Uc, 2us (allowed)
- Tap changer operation - 0.9 .. 1.05 pu (allowed) – under the assumption of a typical change speed of the tap changer (even with compound winding)

The role of the lab environment is twofold. Firstly, the ICT setup has to be developed and validated. Here the real time requirements results from the measurement system performance. Secondly, in order to detailedly define the allowed operation range all thinkable cases of disturbances have to be simulated before such a system can be released for monitoring a real PCC.

VII. CONCLUSIONS

A real time development platform for the simulation of next generation of power system control functions is introduced. After a brief outline of the anticipated power system development with heavy use of information and communication technology requirements for a corresponding laboratory environment have been outlined. The realized simulation platform comprises different modules covering most of the simulation application cases with respect to primary and secondary components and the entire underlying information and communication system. Some reference networks and application examples have been presented in order to demonstrate the functionality of the proposed laboratory setup. With the proposed system a first step towards a “holistic” system simulation has been realized; this in particular against the background of microgrids, smart grids and other domain area where ICT play a major role and may become decisive for stable grid operation.

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IX. BIOGRAPHIES

Michael Kratz (M’05) was born in Germany in 1979. He received his diploma degree in Computer Science Engineering in 2005 at the Ilmenau University of Technology, Germany.

In 2005 he joined the power system department at the Ilmenau University of Technology as a scientific co-worker. He is working on research projects related to design, control and operation of future power system with special interest on communication and information technologies.

Dirk Westermann (M’94–SM’05) was born in Germany in 1968. He received his diploma degree in Electrical Engineering in 1992 and his Ph.D. in 1997 at the University of Dortmund, Germany.

In 1997 he joined ABB Switzerland Ltd. where he held several positions in R&D and Technology Management. He became full time professor and head of the power system department at the Ilmenau University of Technology in 2004. There he has been the director of the Institute of Electrical Power and Control Technologies since 2005. He is author of many international scientific publications and holds international patents for power system planning and control. He worked on research projects related to power system analysis and control and energy management systems. His current research interests are related to design, control and operation of future power systems.

Prof. Westermann is senior member of IEEE, regular member of CIGRE SC B4 and member of VDI. He is actively contributes to the IEEE Germany Section and the IEEE Power Engineering Chapter Germany. He is also convener of CIGRE WG B4.46.