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On the Use of Real-Time Simulation Technology in Smart Grid Research and Development

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***Abstract*- This paper discusses the various aspects involving the research and development of smart grids. Discussed are applications, from large grid renewable integration, WAMPAC systems to micro-grids. Load scheduling and power balance, communications issues, understanding customer behavior, large area protection and distribution control are only some aspects of the challenge of making power grids more robust, more intelligent. The potential complexity of such smart grids requires careful study and analysis before actual realization. This paper explains how such challenges are addressed using real-time simulation technologies in different laboratories around the world.**

I. Introduction

What is a 'Smart Grid' or 'Intelligent Grid'? The Merriam-Webster dictionary defines intelligence as 'the ability to learn or understand or to deal with new or trying situations or the ability to apply knowledge to manipulate one's environment'.

One definition of intelligence also relates to 'information concerning an enemy or possible enemy or an area'. The analogy to smart grid is that information gathering (done through sensors) and communications are critical to achieve good performance 'against' various grid actions or events that can compromise it.

A smart grid can be viewed in two ways: first, from the intelligence of its design to deal with modern challenges like efficiency, reliability and environment. Secondly, from the smart grid's ability to deal with its own complexity, that in return inevitably creates trying situations.

Smart grid therefore means more than simple improved energy efficiency. Smart distribution and transmission grids can include enhanced reliability with regards the grids events or reconfiguration, reduce peak demand, and shift usage to off-peak hours and lower total energy consumption. It can also deal with innovative ways to use customer-generated energy such as solar, wind, and other renewables and re-inject it into the grid as depicted in Fig. 1. The increased use of electric vehicles can also have an impact on the grid, either for charging or for energy reserve of the state's car fleet. Smart grid designers must also have a better understanding of how energy is used by each appliance or piece of equipment.

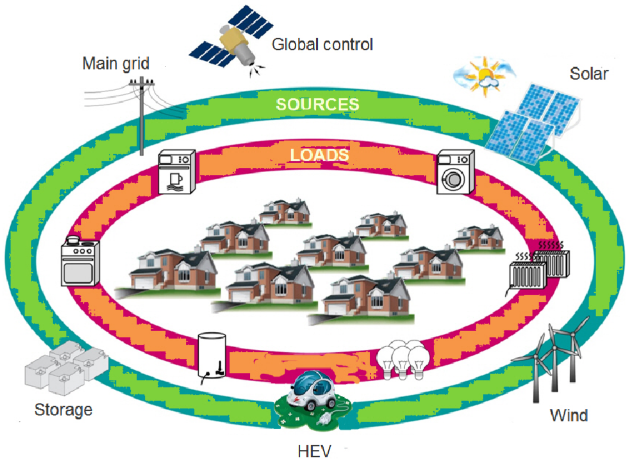

Fig. 1. A smart distribution grid example

The high complexity of modern smart grid design calls for advanced design and testing methods. Real-time simulators can be of great help in this regard, enabling researchers to test complex systems and methods related to smart grid development directly in their laboratories. The main objective of this paper is to demonstrate such applications, using examples of research done at major Universities around the world. Smart-grid research is done through the extensive use of real-time power system simulators.

In this paper, we will discuss the various applications, studied in various research facilities around the world, related to smart grid development using real-time simulator technologies:

- Novel, distributed, grid control methodologies,
- Testing of communication protocols, like IEC-61850 and DNP3,
- Novel approaches to distribution grid state estimation using high discrimination PMUs,
- WAMPAC system development and testing,
- Active filter methods used in connecting various power electronic converters to smart grids,
- Large Area Renewable Integration,
- Power-HIL simulation techniques,
- Real-time phasor simulation.

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II. Smart-Grid and Communications

Communication links are critical to correctly co-ordinate the working behavior of power grids. For example, in classic power grid topologies, consisting of a relatively small number of synchronous production sources connected to loads, communication of phasor measurement units was already mandatory to operate the grid.

Modern, greener grids, by contrast, are made of much more active devices. These grids are designed to allow the incorporation of many power sources, such as wind turbines and solar power, whose behavior is much more difficult to predict. Smart grids can also use various energy storage devices on the grid, like electric cars connected to the network.

All these new features and capabilities critically depend on proper coordination and communication. For example, IEC-61850 is an IP-based communication protocol that is rapidly gaining acceptance in the power industry. It was originally designed for protection and sub-station control but can be adapted to deal with the complexity of smart grids.

The RT-LAB simulator supports the IEC-61850 and DNP3 protocols and enables users to test different control strategies using this communication protocol.

This type of study involving the IEC-61850 protocol is being investigated at KTH Smart-TS Laboratory, in Stockholm, Sweden. The IEC-61850 protocol implements the data transfer between primary equipment and IEDs through Ethernet network. The protocol has two main components: GOOSE, for the transmission of digital data like trip signals, and Sampled Values, used to transmit analog values such as currents and voltages. Use of IEC-61850 based relays eliminates the need for costly copper wires and facilitates interoperability between equipment from different vendors in a substation. The reliability of the IEC-61850 protocol is still being analyzed and pilot projects have been implemented world-wide to evaluate its performance as compared to traditional copper wiring architecture.

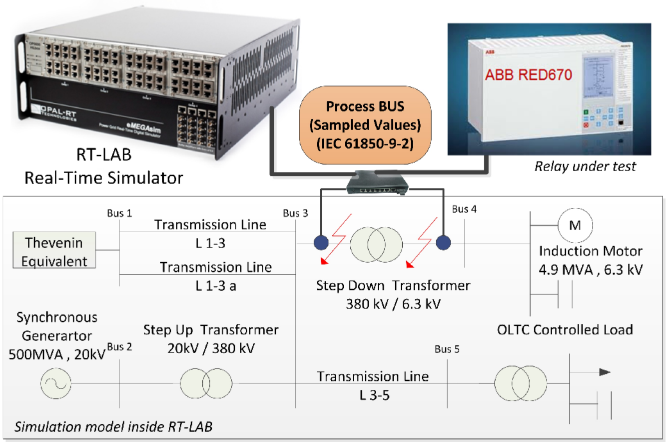

Fig. 2. IEC-61850 testing using RT-LAB

At KTH, a real-time Hardware-in-the-loop approach for assessing protection features with IEC-61850 was used[1]. As described in Fig. 2, differential protection feature of ABB RED-670 is evaluated for a two winding transformer model executing in real time using eMEGAsim, OPAL-RT's real-time simulator. An extensive testing procedure of Schweitzer's SEL-487E relay with IEC-61850 and the RT-LAB simulator relays was also done in [14].

III. Cooperative Filtering in Distribution Network

Researchers at Universidade Federal de Campina Grande (UFCG), Paraíba, Brazil, have been using the RTDS simulator, from RTDS Technologies, Canada, and more recently the RT-LAB simulator from OPAL-RT Technologies to study various smart grid challenges, such as cooperative control of multiple active filters based on voltage detection and Total Harmonic Distortion (THD) computation to improve power quality.

The time changing of loads, shunt capacitors, faults or others that occur in real electric power system is not fully predictable. These time-variable scenarios can benefit from a distributed control in which several Active Power Line Conditioner (APLC) cooperatively reduce harmonics from all Points of Common Coupling (PCC) in the power system. The objective is to make sure that harmonic reductions meet the IEEE-519 standard, which states that the THD value should be under 5%. In [2], APLC controllers were implemented in DPS processors from Texas Instruments and interfaced with the real-time simulator to verify their effectiveness in real-time.

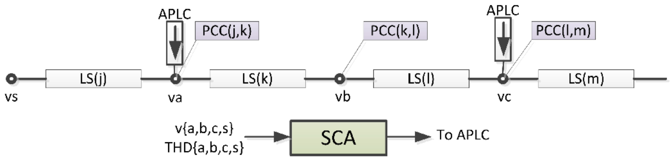

Fig. 3. Simplified representation of a power distribution network and the proposed APLC control scheme

The proposed APLC control scheme for power distribution networks is depicted in Fig. 3. In the figure, 'LS' denotes a power distribution line segment, 'PCC' denotes a common coupling point, 'Nc' denotes a local node controller installed at PCC, APLC block denotes the PCCs that have compensation and SCA denotes the central supervisory control automation. The local voltages and currents are acquired by the node controller. The voltage THD is then transferred to the SCA. The APLC block has a local processor that implements the APLC control law based on a reference current provided by the SCA.

One important finding of the research was that using fewer APLC than power electronic loads still respects the IEEE-519 norm, provided that that the location of APLC is correctly chosen and that they work in concert.

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IV. Agent-based distributed control of smart grids

These days, the important integration of electrical wind power production at the distribution network may induce some problems on voltage regulation. One reason is that the existing distribution grid was not designed to include this type of energy production. For example, the connection of wind generators in a distribution network may cause local over-voltage and affect the correct operation of On Load Tap Changer (OLTC) transformers.

Different secondary voltage regulation strategies in distribution networks have been proposed in the literature. In most cases, the voltage regulation schemes are centralized and performed through a central computer that supervises all the distributed generator production (e.g. wind generators) and optimally adjusts the voltage set points of these distributed generators. An example of this control principle is Distribution Coordinated Voltage Control (DCVC) which is an adaptation to the distribution network of the coordinated control used in some transmission networks [29][30]. This centralized regulation algorithm must know the whole network configuration and also needs a high number of components to perform both data acquisition and system communication. It solves a unique optimization function that must be recomputed if a source is connected or tripped. However, for the large-scale development of many distributed generators, it may become difficult to perform a centralized system control. Lots of events and/or modifications may arise in a distribution network and the limits of a centralized control system may be reached quickly.

Using a real-time simulator, researchers at the L2EP Laboratory in Lilles, France, are working to develop a decentralized method for voltage control in a distribution network. Each source is solving its proper optimization function based mainly on local information. A very simple coordination method is proposed that allows easy integration of a new source in the overall voltage control. This method is based on the concept of Multi Agent System (MAS) [3][4].

In their experiments, they coupled the RT-LAB simulator with 3 independent 'Agent' programs. Each of the Agents had to control the voltage and power level at their own wind generator point of connection in the grid. The grid was simulated in real-time in the real-time simulator using the SimPowerSystems blockset and the ARTEMiS real-time plug-in from OPAL-RT. The Agent controllers and the simulated grid interacted through TCP/IP links.

Shown in Fig. 4, researchers developed a platform dedicated to the study of distributed energy control and the behavior of future electric networks. It includes various sub-platforms that can interact with the RT-LAB simulator, namely a JADE platform for Agent code development [5] and a SCADA monitoring tool.

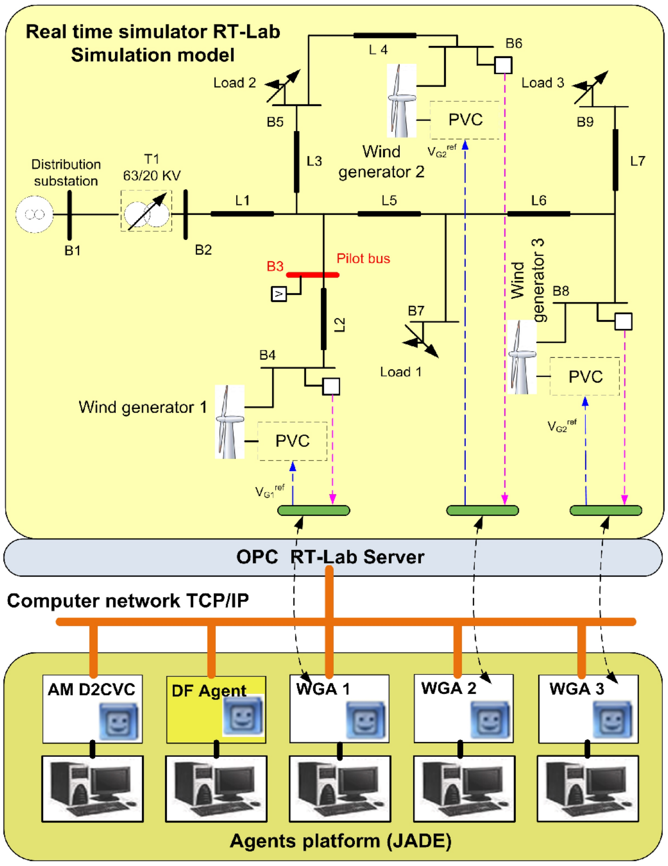

Fig. 4. Multi-Agent smart grid test platform using RT-LAB

V. Real-time simulation of distribution grids

Incorporation of renewables into the distribution grid poses new challenges in terms of required processing power to perform real-time electromagnetic transient simulation. This is an aspect of real-time simulation that is being studied in a joint effort by the G2Elab at the Grenoble Institute of Technology and the L2EP of University Lille Nord de France, both located in France.

One of the main reasons for this is that, as opposed to 'classic' power systems that span large geographic distances, distribution networks are lumped by nature. This implies that classic equation decoupling methods for real-time simulators, like the use of Bergeron-type lines, cannot be easily used on this type of network.

In [6], the distribution network of Fig. 5 was simulated in real-time. This power network has 210 buses, 210 lines and 121 loads, separated in 5 main sub networks joined together at the OLTC feeder.

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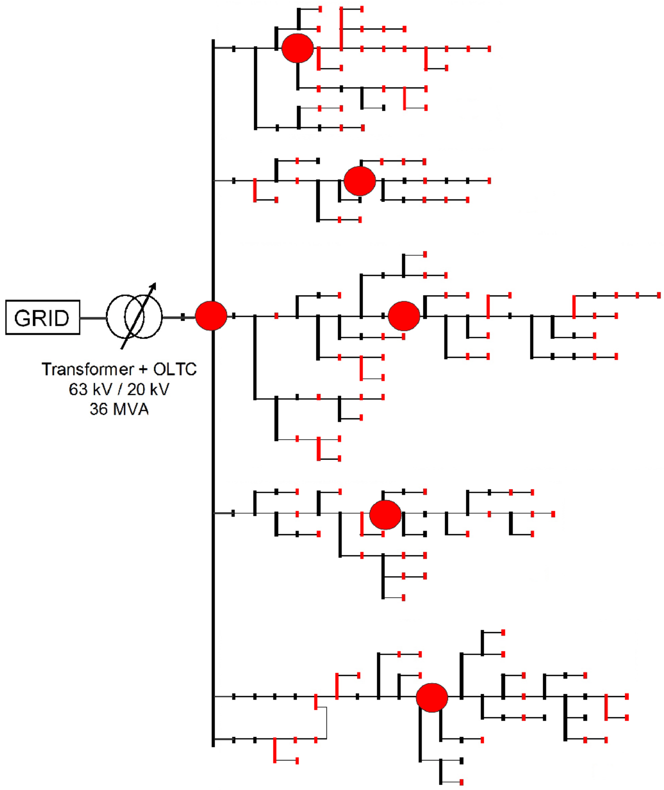

Fig. 5. Distribution grid with renewable integration

The total length of the lines is about 68 km for an average length of main lines of about 7.5 km, which is too short to allow equation decoupling by using transmission line natural propagation delays.

To perform the real-time simulation of such a network, one must either

1) add delays with 'compensated delay method' [6] or
2) use a simulation solver based on virtual decoupling/partitioning such as ARTEMiS-SSN that does not induce any delay in the solution.

In [6], a manual compensated delay method was used with success, resulting in error less than 0.002% in active and reactive powers (compared with a simulation without delays). The achieved real-time simulation time step was 50 µs. It is worthwhile to explain here that the delay approach was used successfully because the power flow control was the main objective of the paper. In the case of fault studies, it is NOT possible to use delay-based methods without inducing important inaccuracies in the transient responses. In this case, a delay-free solver like EMPT or SSN is required.

A. *OLTC modeling in SSN using User's Custom Nodal Code (SSN External models)*

Typical distribution systems used several transformers with on-line tap changers (OLTC) to regulate the voltage. The real-time simulation of such systems poses a challenge since OLTC simulation is usually implemented using about 16 switches per phases. The state-space system must therefore be recomputed each time OLTC changes positions. Such re-calculation may cause processing time overruns, unless the simulation time step is increased, which is not always possible in order to maintain numerical stability and accuracy. Using SSN external model' feature [26] allows direct coding of an OLTC equation in the discrete domain *with any number of taps* without overloading the processors since that it is no longer necessary to recompute the state-space matrices of the total system. Indeed, in the discrete domain, an OLTC is simply a transformer that has a variable turn ratio and leakage inductance.

More generally, the SSN (State-Space Nodal) algorithm [7] creates virtual state-space partitions of the network that are solved simultaneously using a nodal method at the partition points of connection. The partitions can be solved in parallel on different cores of a PC *without delays* in the algorithms.

B. *Delay-free SSN simulation of distribution grids*

In [9], it was demonstrated that the SSN solver allows the real-time computation of a bipolar HVDC link with several switched filter banks without any delays or stublines.

With recent code optimizations, the model presented in [6] (composed of 650 nodes and nearly 400 states and 750 measurements) can now run below 60 µs time step, *without any delay in the solution.* To achieve this performance for this rather large distribution system model, the SSN algorithm creates 13 groups (or partitions, or multi-terminal branches) connected to 18 nodal connection points.

A similar radial distribution system with more than 700 nodes (with 980 L-C states from short pi-lines) was also simulated recently at a time step under 65 µs, without algorithmic delay or stub lines, using 4 cores of a 3.33 GHz Xeon multi-core server running RT-LAB. This performance is possible because the SSN reduces the network into a system with only 6 nodes and 6 multi-terminal branches (i.e. SSN groups) and uses threaded process to compute the SSN group equation in parallel, without any delay.

Further algorithmic enhancements are also planned for the LU solution side of SSN. In the current version of SSN, the SSN groups (or partitions) are allocated to the available cores with a simple computational load balancing without regard to the 'locality' of computations. In the current implementation, the complete LU solution is also made on one core.

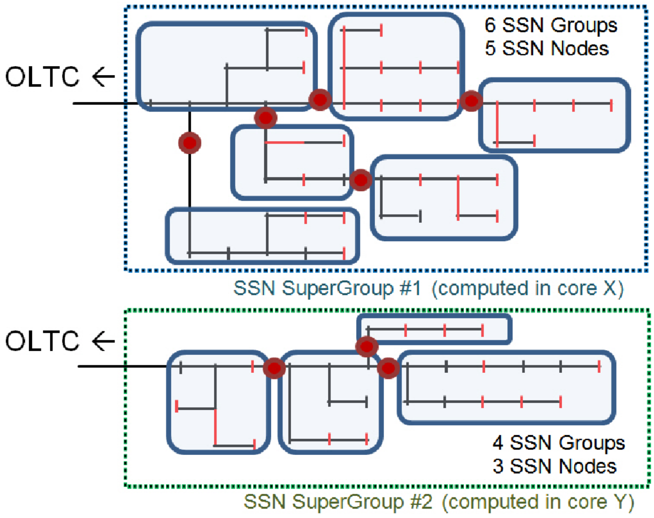

Fig. 6. Two-level node tearing method in SSN

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Efforts are made to implement a 2-level node tearing method in SSN in which co-called 'SSN SuperGroups', corresponding to large sets of highly coupled SSN groups are assigned to a specific core. The technique also requires the parallelization of the LU solution across the cores. Reference [8] provides a good explanation of how this can be done.

Fig. 6 explains this 2-level tearing method on the OLTC-fed distribution network (shown for 2 SSN SuperGroups only). This case is a good example because of the star configuration of this network; there is a natural tearing point at the OLTC connection point where all 'SuperGroups' connect. This leads to minimal inter-core communications. The standard SSN groups are still required in this approach to minimize the overall number of nodes used in the LU and pre-compute the group equations with regards to switches within the groups.

VI. Real-Time State Estimation of Active Distribution Network

Within the context of active distribution networks, people at the Distributed Electrical Systems Laboratory (DESL) of EPFL, Switzerland are using a Real-Time platform with the aim of developing an RT state estimator that we will use for real-time optimal voltage control and fault detection and location.

At the base of this real-time platform, an OPAL-RT eMEGAsim simulator is used to implement a distribution network model with unbalanced lines and dynamic loads, like the IEEE 13 bus test feeder. The RT simulator also computes the power injections in all the nodes in correspondence with GPS-PPS events, which are sent to the simulator by a dedicated PMU. The RT-computed powers are streamed by the RT simulator to a phasor data concentrator (PDC) via the 61850 protocol. The PDC is based on the OpenPDC platform.

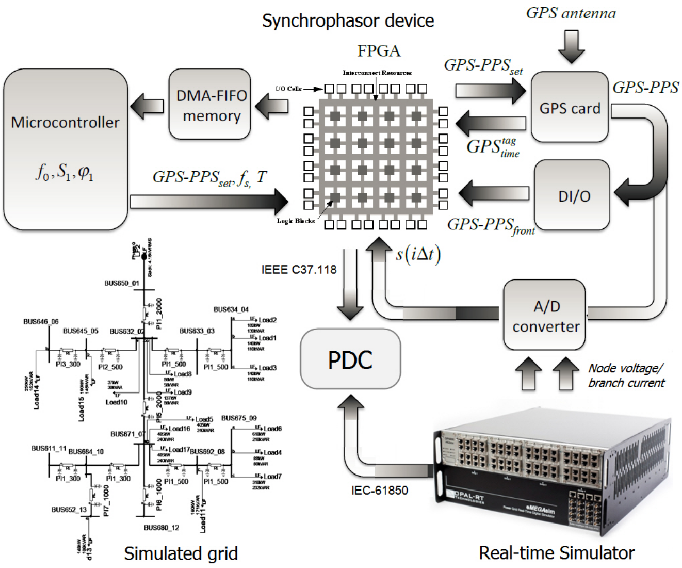

Fig. 7. Synchrophasor device testing with a real-time simulator

The PDC collects data from the PQ measurements (provided by the real-time simulator) and from PMUs, creating a RT database that is updated every 20 ms (both PQ and PMU measurements are streamed every 20 ms). Notably, the system allows the RT simulator to time stamp its measurements with an external GPS source. Network state estimation is made from this database using Kalman-filter based estimator [13].

VII. WAMPAC Systems Development

One of the objectives of the KTH Royal Institute of Technology is to develop new and advanced Wide-Area Monitoring, Protection, and Control System (WAMPAC). At the core of the development of "Smart Transmission Grids" is the design, implementation, and testing of synchronized phasor measurement data applications that can supplement WAMPAC. In [15], Statnett's Software Development Toolkit (S^3DK) was introduced, which can be used to implement new WAMPAC applications. The S^3DK was validated against off-the-shelf WAMPAC software using the OPAL-RT eMEGAsim real-time simulator by interfacing it with PMUs and PDCs from Schweitzer (SEL). The S^3DK provides a platform for developing monitoring and control applications. The S^3DK consists of a real-time data mediator and a suite of functions implemented within a LabView library that enable sorting and managing phasor data, and moreover, to implement new applications. In [15][16], two applications are presented, a wide-area monitoring tool and an on-line mode estimation tool, respectively.

A. Wide-Area Monitoring Tool for Desktop and iPad

The Wide-Area monitoring tool developed using S^3DK is able to display the operation status of different PMUs in a university-based PMU network at different universities in Scandinavia. The application allows to display the frequency, voltage, and any other phasor quantity of the network. Furthermore, the application can provide alarms when the frequency goes below specified thresholds.

Fig. 8. Wide-area frequency monitoring application in Statnett's Synchrophasor Development Toolkit

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Because the S^3DK is integrated within the LabView environment, this facilitates porting it to iOS devices using tools from National Instruments. The same application runs in a server that can provide the calculated alarms and selected display values to iOS-based devices. Fig. 8 shows a screen output for the iPhone and iPad.

B. *On-line Electromechanical Mode Estimation*

The on-line mode estimation application is based on work outlined in [16] where archived data is used to estimate electromechanical properties of power systems. The application collects real-time measurements for a pre-specified time window and then processes these measurements in two steps, using a spectral estimation. A screen shot of this application is shown in Fig. 9.

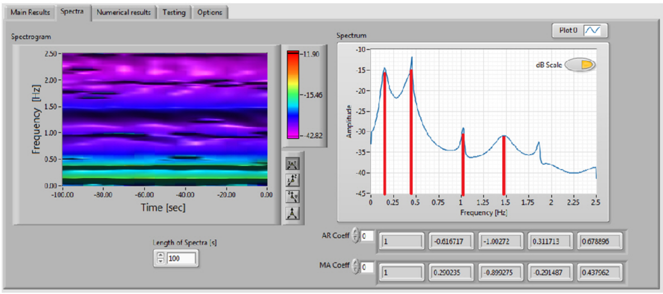

Fig. 9. KTH on-line mode estimation application built using Statnett's Synchrophasor Development Toolkit

VIII. A Smart-Grid Laboratory with Power-HIL

In [17], a Japanese consortium set up a laboratory to study micro-grids. This laboratory includes a real house connected to a 10-kW power amplifier interfaced with a distribution network simulated with the OPAL-RT's eMEGAsim power system simulator in a Power-Hardware-In-the-Loop (power-HIL), as depicted in Fig. 10.

The house is equipped with appliances and other equipment, including fuel cell, photo-voltaic systems and other equipment that is being contemplated for future houses. These houses will be integrated into modern micro-grids where each house could also return energy to the grid.

Such distributed energy distribution and generation systems will become very complex due to possible interactions between intelligent equipment located in each house and with the power grid. For example, the behavior of the system when disconnected from the power grid must be determined. Frequency control in disconnected or faulty modes is also a subject of research.

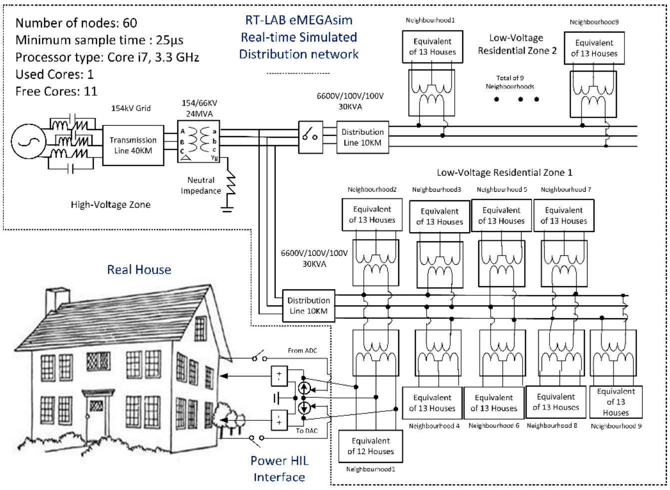

Fig. 10. Smart-Grid power-HIL laboratory with real house

The Microgrid Laboratory will enable analysis of such interactions between the power grid and house equipment by injecting the house current to the feeder circuit simulated by the eMEGAsim real-time simulator, which in turn will return the feeder voltage to the house with a power-HIL connection.

Stability of power-HIL simulation set-ups is of special concern. The simulator, amplifier and house form a closed-loop system that may become unstable under certain operating conditions, like any other closed-loop systems. Such stability problems have been studied in literature [18][19].

IX. Renewable Unitary Testing Using Power-HIL

Researchers at the GE2LAB in Grenoble use a hardware-in-the-loop test bench designed for assessing photovoltaic control unit performances. The photovoltaic panels, coupled with a boost circuit, are software-simulated within a real-time environment, RT-LAB, and coupled in closed loop with the controller unit to be tested [20].

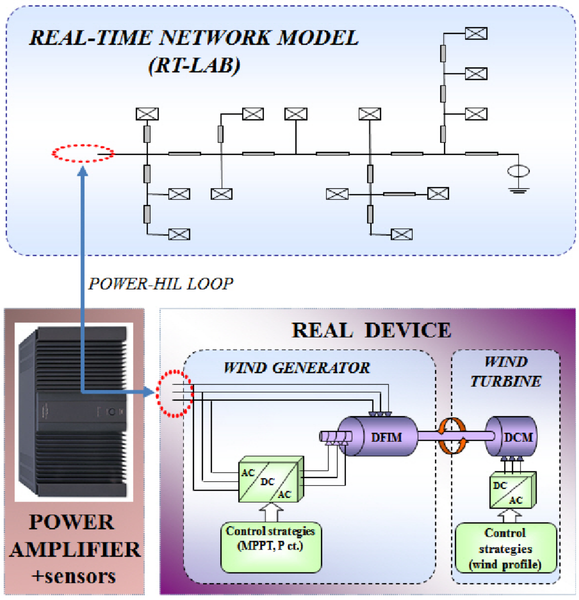

Fig. 11. Power-HIL bench for wind-generator tests

In [21], they also used power-HIL simulation to design a wind-turbine bench. In this bench, a wind-turbine is controlled with its shaft connected to a 2nd machine that emulates the wind torque. The xPC Target simulator was used to simulate the wind action on the DC machine, while a dSpace real-time simulator was used to control the DFIM inverters. A more sophisticated bench set-up, described in Fig. 11, involved the real-time simulation in RT-LAB of a complete grid in interaction with a real DFIM wind turbine[22]. Protection systems were also tested using a similar methodology [28].

Researchers at the Austrian Institute of Technology (AIT), Vienna, Austria, are also studying renewable integration into grids using PHIL simulation. They use the real time simulator for various investigations on low-voltage distribution networks such as photovoltaic power source integration on the grid, as depicted in Fig. 12. Various grid impedance scenarios, which are of interest and under investigation, are implemented in the simulation model and run on the real-time computing machine. Thereby, active/reactive power (P/Q) control strategies are emulated in the simulation and their impact on the grid stability/quality is determined.

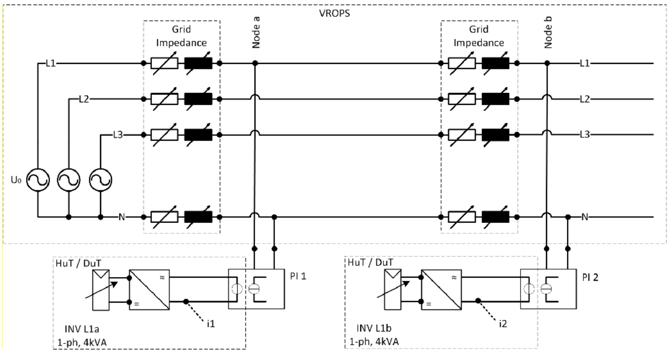

Fig. 12. Power-HIL study of photovoltaic integration

The whole electrical system is run on RT-LAB and, apart from the PV array simulation (emulation of solar panels), grid connected PV inverters and peripheral measurement equipment, all components are implemented in software. The overall simulation system bandwidth is set to 1 kHz, which is a good compromise in simulation stability and accuracy for the investigation of PQ scenarios typically featuring quite slow time constants in the range of milliseconds. The two power interfaces (PI) are implemented as classical ideal transformer model (ITM) or multi rating (MR) algorithms, because the filter component values of the PV inverter model are not fully known in detail. AIT is using a full linear AC amplifier as a high-fidelity power amplification unit and LEM PR30 clamps for the feedback current measurement. Use of the PR30 current probe is sufficient to obtain good accuracy, dynamics and stability of the Power-HIL simulation[23].

Of particular interest are the coordinated effects of the reactive power control of the PV inverter with regards to various grid impedance configurations. In Fig. 12, the implemented grid impedances from the grid to node *a* are set according to a relatively low value (standard impedance according to EN61000-3-3) while the impedances between node *a* and *b* are chosen significantly higher. The effect on the inverter connected to node b should be stressed in order to observe modifications in the magnitude of the voltage. Many other scenarios - consisting of multiple PV inverters connected to different nodes having various reactive power control parameter settings – have been implemented in order to investigate the limits of regular mode, permanent oscillation or instabilities of the reactive power control.

X. Renewable Integration in Very Large Grids

As depicted in Fig. 13, the province of Quebec's grid is much dispersed geographically and requires many power electronic devices to stabilize and control it properly. It is notably connected asynchronously with a multi-terminal DC-link to the USA and back-to-back converters to the province of Ontario. The long distance between the production site in the North and consumers in the South forces the use of Static VARS Compensators (SVC) along the 735kV lines. In addition, the North-South orientation makes the network prone to solar-storm defaults and these lines are therefore series compensated. This unique complexity requires thorough testing methods of controls and protection systems using a real-time simulator interfaced with control system replicas.

In [10], the complete power network of the Province of Quebec, including 25 new DFIG-based wind power plants in the Gaspé region of Quebec, was simulated in real-time on the Hypersim Real-time simulator. The network contained the following elements: 643 three phase buses, 34 hydroelectric generators (turbine, AVR, stabilizer), 1 steam turbine generator, 1 multi-terminal DC-link, 25 Wind Power Plants with DFIG generators, 7 static VAR compensators, 6 synchronous condensers, 167 three-phase lines and 150 3-phase transformers with saturation modeling. Hypersim used 72 processors of an SGI super-computer to make the real-time simulation of this network at a time-step of 50 µs

Fig. 13. Province of Quebec power grid with renewable sources in the Gaspé region.

XI. Phasor-Mode Real-Time Simulation

With the ever increasing demands for power system reliability, testing requirements are expected to rise accordingly. In distribution networks notably, the number of electric nodes can easily exceed the capability of standard electromagnetic transient (EMT) real-time simulation approaches. With this in mind, OPAL-RT is currently developing a real-time simulation solution called ePHASORsim based on phasor-type solvers [24][25].

ePHASORsim can simulate systems in the range of 20,000 buses faster than real-time at time step of 10 milliseconds. This technique is very well suited for HIL real-time simulation applications required to test global power system control and protection systems implemented in modern SCADA. This phasor solver uses the explicit two-step Euler integration method to discretize the differential equations in order to achieve such performances. Moreover, sparse matrix solutions have been exploited efficiently to factorize and solve network nodal equations.

The real-time Phasor simulation method is now used by a large SCADA system manufacturer to test local and wide area control software using a DNP3 interface. Such a method is efficient to test control of very large power systems for cases where the simulation of fast electromagnetic phenomena is not required. Research is underway to simulate even larger systems using parallelization methods similar to the ones used in SSN.

Conclusion

This goal of this paper was to show how real-time simulators are used in smart-grid research laboratories around the world. Many interesting applications have been reported, such as IEC-61850 testing, grid state estimation, distributed grid control, WAMPAC system development, cooperative active filtering and large grid renewable integration testing. The use of real-time phase-mode simulation of very large system was also reported

XII. Acknowledgments

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