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Real-time hybrid facility for the study of distributed power generation systems

D. Ocnasu[1], C. Gombert[2], S. Bacha[1], D. Roye[1], F. Blache[1] and S. Mekhtoub[3]

[1] Electrical Engineering Laboratory, Institut National Polytechnique de Grenoble 'INPG', France
[2] Thales Avionics Electrical Systems, Paris, France
[3] Laboratoire d'Electrotechnique, Ecole Nationale Polytechnique, El Harrach, Algérie

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Abstract - *The presence of renewable energies on the distribution grid is continuously evolving, influencing more considerably the overall comportment of the power system. The intermittent character of the primal energy (wind, sun, water) increases the complexity of the problem, thus new test facilities must be developed. As power electronics are generally part of these production systems, high frequencies are involved so the test facilities must be well adapted. The present paper proposes the Real-Time (RT) Hybrid Simulator as a very flexible test facility, well suited for the study of grid connected electrical devices.*

Résumé - *La présence des énergies renouvelables sur le réseau de distribution est en constante évolution, pour influencer plus considérablement le comportement global du système électrique. Le caractère intermittent de l'énergie primaire (vent, soleil, eau) augmente la complexité du problème, donc de nouvelles installations d'essai devront être développées. Comme l'électronique de puissance fait généralement partie de ces systèmes de production, les hautes fréquences sont aussi concernées les installations d'essais devront être bien adaptées. Le présent papier propose le système hybride en temps réel comme un simulateur très flexible comme installation d'essai, bien adapté pour l'étude du réseau électrique des dispositifs connectés.*

Keywords: Distributed generation (DG) - Real-time hybrid simulation - Hardware-in-the-loop - Power-hardware-in-the-loop - Renewable energies.

1. INTRODUCTION

In the past, the power generation used to be connected to transmission level. Today several producers are connected at distribution level (distributed generation 'DG'). The power grid was initially conceived to carry the energy from the transport level, where the majority of the producers were connected, towards the consumers. Therefore, the first problem that comes into view, once with the introduction of the DG, is the modification of the power flow. This has severe consequences over the voltage plan as well as on the protection and control plan.

Further more, mostly due to the environmental policy [1], the wind energy and other renewable types of generation (photovoltaic, micro-hydrogeneration, etc.) have an increasing place.

The proposed approach shows its interest when it is desired to study the interaction between different producers, and between the producers and the grid (harmonics disturbances, voltage dips, frequency fluctuations, islanding, etc.). By using a RT hybrid simulator, some producers can be real (analogical) and some of them can be numerically modelled. This way a perfect compromise is achieved between accuracy, flexibility and size of the resulting test bed.

Industrial devices (e.g. PV inverters) or prototypes are often ‘closed’ (with classified content) and therefore impossible to numerically model. By using a RT hybrid simulator, they can be studied as ‘black-boxes’ as they were in their real operating conditions.

This article presents several essential aspects that must be taken into consideration at conception and exploitation levels of a RT hybrid simulator (sampling times, delays, accuracy, interface equipments characteristics, etc.).

Several applications are presented in order to prove the high flexibility of such a simulator and its large area of applicability.

2. REAL-TIME HYBRID SIMULATION’S BASICS

2.1 General description

A RT hybrid simulator is composed by two main distinct parts: a RT digital simulator, respectively an analogical part. In our case, the RT digital simulator is ARENE URT, a simulator developed by EdF (Electricité de France), running on a UNIX platform using a HP-J5600 552 MHz bi-processor computer.

Depending on the type of the signals that are exchanged between the numerical and the analogical part, two categories of RT hybrid simulation can be distinguished (Fig. 1):

- HIL – *Hardware-In-the-Loop*, only control signals being exchanged. This method is usually used for the test of controllers [2-4] or protection systems [5-8].

- PHIL – *Power-Hardware-In-the-Loop*, real currents and real voltages being present in the benchtest. As it will be seen as it follows, this method is the perfect way to test physical devices as close as possible to their real operating conditions.

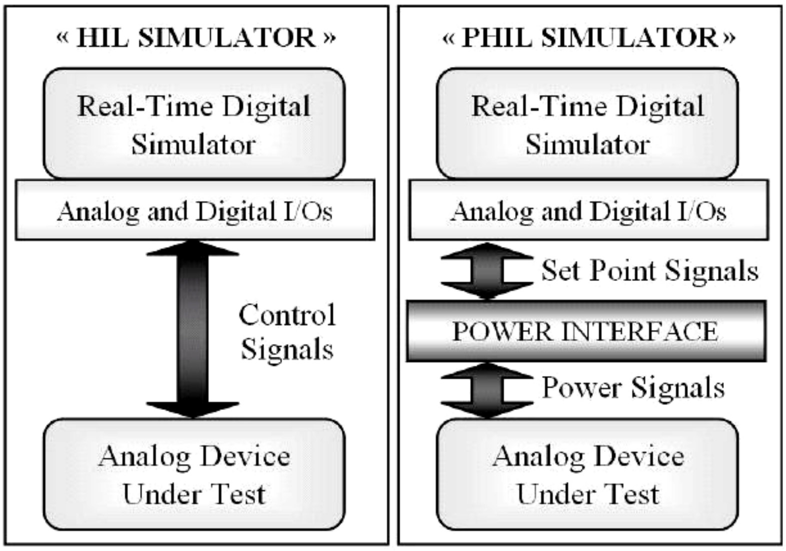

Fig. 1: Comparison between HIL and PHIL simulators

As it can be seen in figure above, the power interface is a key element of the PHIL simulation. Its first role is to obtain the power signals from the set points, by the use of a power amplifier. The second one is to make the analog device under test visible for the digital simulator, by the use of several captors.

In the case of HIL simulators a power interface is not necessary. However, in the case of power electronics applications, when PWM (Pulse Width Modulation) methods are involved, high sampling rates are need and therefore high calculation performances. If the digital RT simulator does not present such performances, an alternative solution can be adopted by the use of a 'hardware interface' [9].

The RT digital simulator can be used for example to model a power system, which would be difficult to replicate analogically due to the size of the resulting benchmark. Depending on the desired application, several signals (proportional with the simulated voltages, currents, etc.) can be outputted.

By using the power amplifiers, the calculated values (outputted by the RT digital simulator) are transformed in real voltages or currents and applied to the analogical part. The power amplifiers must permit both types of control: current or voltage in order to have a more adaptable PHIL simulator.

The analogical part allows simulating equipments of characterized by heavy models which are not suitable for RT simulation (devices based on power electronics having high switching frequencies relatively to the simulation sampling time, rotating machines, etc.). Another advantage is the possibility to test industrial devices by considering them as 'black-boxes'.

In order to close the real-time loop different sensors are used, allowing the insertion of different measured values into the RT digital simulator.

It is a fact that a real/analogical device is always more trustful than a numerical model regarding the replication of all the phenomena that can occur during their operation. Therefore, a RT hybrid simulator is undeniable more reliable than a fully digital one.

It can also be said that the RT hybrid simulators eliminate the lack of 'realism', which is a disadvantage of the digital simulators. Actually, the analogical part can consist in rotating machines, real voltages and currents, while a digital simulator brings out only data files.

In the same time, some inconveniences of analogical simulators are also eliminated, like the simulated grid's dimension, which can be more significant on the digital part. Moreover, it is simple to make parameter changes and to create disturbances (voltage drops, frequency fluctuations, etc.) on the simulated grid; only 'by keyboard', no physical device must be replaced.

In other words, by digitally simulating part of the components while the other part is real/analogical, a perfect compromise is achieved between accuracy, flexibility and size of the resulting test bed.

2.2 Real-time digital simulator considerations

As mentioned above, a RT digital simulator is one of the main components of the RT hybrid simulator. Therefore, even if some essential (theoretical and practical) aspects, that are presented as it follows, seem to refer only to the first one actually they refer to the whole.

2.2.1 Connection types

Every electrical power device can be modelled in HIL facilities by a voltage/current source, depending on its connection type. There are two manners to connect a power device to the grid: shunt and serial (Fig. 2).

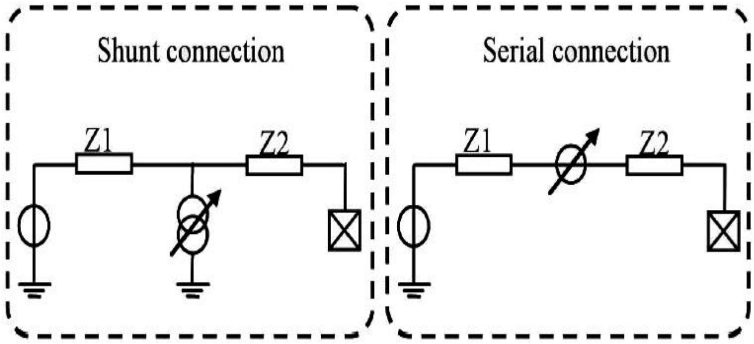

Fig. 2: Shunt and serial connections modelling

The *shunt* connection can be adopted when modelling power generators or loads. Other applications using this type of connection are: for the transmission level - reactive energy control and voltage level control, while for the distribution level - active filtering, flicker effect reduction, load balancing, etc.

In order to obtain such a configuration in PHIL simulation, the power amplifier must be voltage controlled and current captors are used to close the real-time loop. On the digital part, the analogical device is modelled by a shunt connected controlled current source (Fig. 3), the control signals coming directly from the current sensors via analog/digital converters.

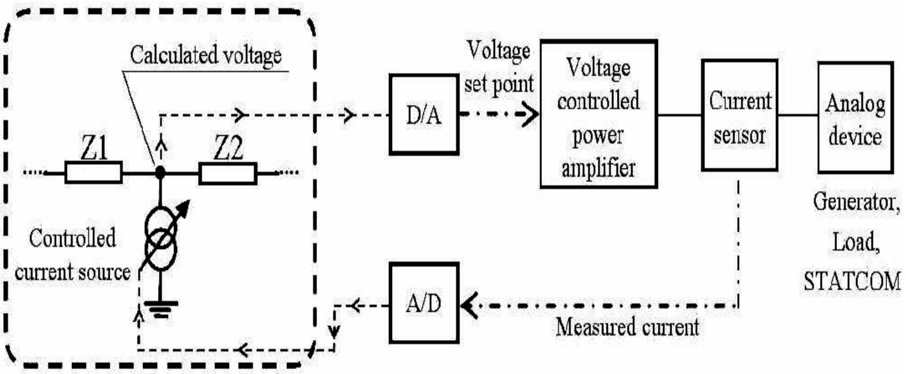

Fig. 3: Shunt connection modelling for RT hybrid simulation

The *serial* connection can be used at transmission level for the load flow control, and at distribution level for: voltage drops reduction, the phase unbalance reduction, the voltage's harmonics compensation, etc.

This configuration is obtained by current controlling the power amplifier and by using voltage sensors. On the digital part, the analogical device is modelled by a serial connected controlled voltage source (Fig. 4).

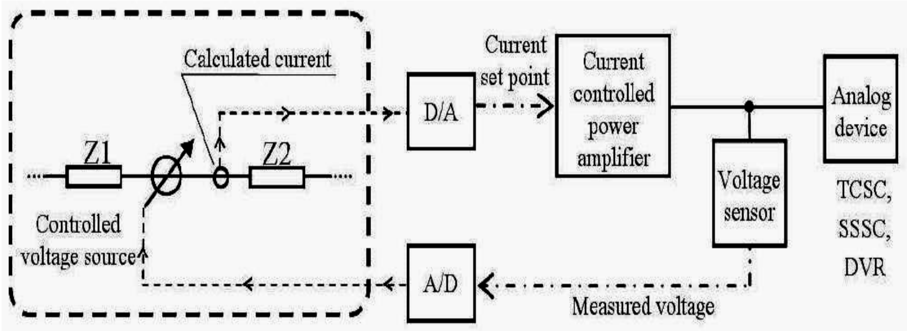

Fig. 4: Serial connection modelling for RT hybrid simulation

2.2.2 Sampling time

The sampling time for a RT simulator is always fixed and does not evolve during the simulation, unlike the case of non-real-time simulators. The sampling time's choice has to be made by the user before starting the simulation. A great attention must be accorded to this step, as several aspects should be taken into consideration:

- a too big sampling time: can decrease the accuracy of the simulation, can increase the delays in the real-time loop (2.2.3), can reduce the frequency band of the simulator (actually the sampling time fixes the frequency domain of the RT simulation, from the Shannon theorem, as in (1); for example, a typical simulation sampling time of 50 µs allows a frequency band comprised into 0 Hz and 10 kHz; for a sampling time of 100µs the frequency band reduces at 0 Hz-5 kHz);

$$\text{frequency band} = \frac{1}{2 \times \text{sampling time}} \tag{1}$$

- a too small sampling time: can make the RT simulation unfeasible; in order to achieve RT simulations, the simulator has to perform *data acquisition, computations* and *data restitution* before the end of each sampling time (Fig. 5.a); if the acquisition and restitution times are rather constants (they depend only on the I/O boards), the computation time can change and depends mainly on the simulator computing power and on the dimension of the equations sets (power system topology and electrical devices characteristics) [2]; whether the three tasks can not be performed during a sampling period (e.g. a topology change occurs during the simulation and the computation time increases) the RT simulation can no longer be realized (Fig. 5.b).

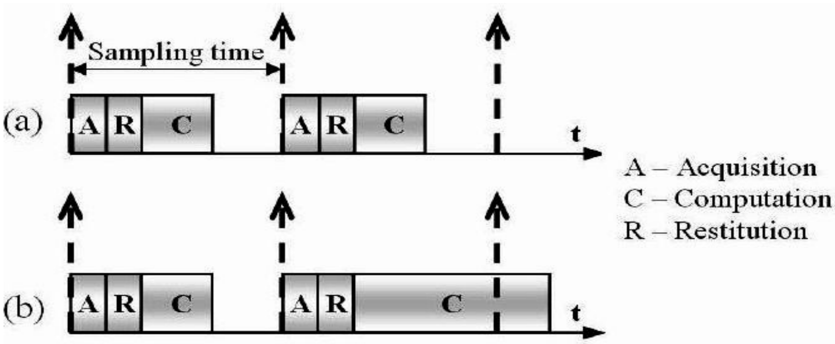

Fig. 5: RT simulator's tasks: (a) feasible and (b) unfeasible RT simulation

2.2.3 Delays

During the tests that have been carried out, a medium delay of two sampling times was always present. In Fig. 6 it is represented the delay for several sampling rates (diagram experimentally obtained for ARENE URT).

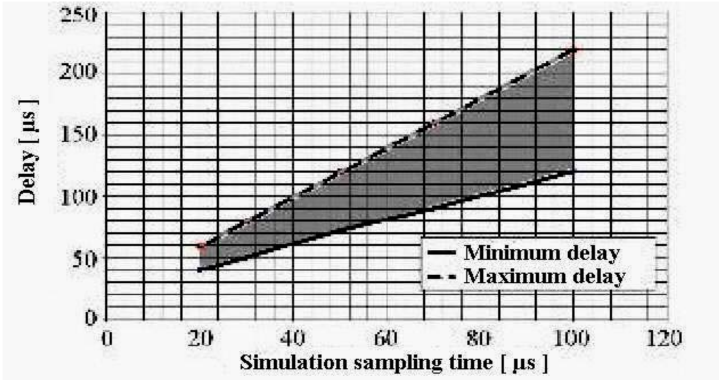

Fig. 6: Delay's variation for different sampling time values

As it can be seen the delay varies between 1 and 3 sampling times. This delay is the time period during which an input signal is sampled, treated by the simulator and restituted at output. The difference between minimum and the maximum delay is comprised between 0 and 1 sampling time (ST) and it can be explained by the Jitter effect (caused by the fixed sampling time sampling). As it can be seen in Fig. 7, this random delay manifests itself by a deformation of the sampled signal [10].

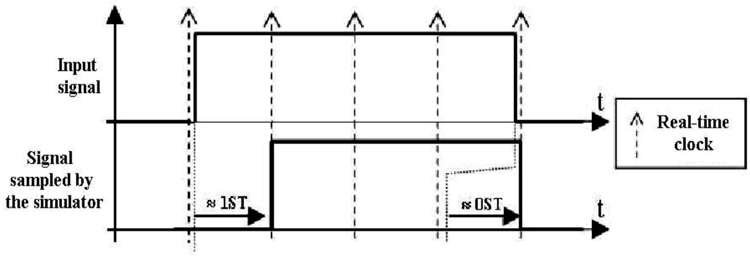

Fig. 7: Representation of Jitter effect caused by fixed sampling time

As a result of its random character, the compensation by simulation of this delay is not accurate.

The above presented delays can have serious consequences in device simulations that need an increased accuracy at the acquisition of the control sampling times. For example, in the case of a full wave operation three phased source converter, the actuating signals must be taken into consideration with a great accuracy, as measurement uncertainties of the switching times between two sampling instants can generate significant result's errors.

2.3 Power interface considerations

As presented in Figure 8, the power interface consists in power amplifiers and several sensors (current sensors, voltage sensors, speed sensor for rotating machines, etc.), making possible the connection between the digital and the analogical parts.

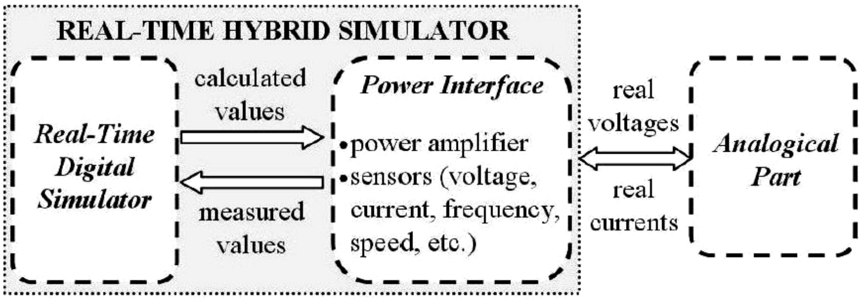

Fig. 8: Schematic diagram of a RT hybrid simulator

Several criterions must be considered in order to proper choose these elements:

- their rated and maximal data must be perfectly known in order to dimension correctly the analogical part; a total concordance should exist between the rated voltages and powers of the amplifier, the sensors and other analogical devices (loads, generators, cables, etc.); if this concordance is not satisfied, saturations of the simulated/measured signals can occur due to the protection systems of these equipments; the precision of the RT simulation is therefore severely affected;

- a compatibility must be always present between the voltage ranges of the digital RT simulator's I/O boards and the amplifier's set point or the sensor's output;

- each element must have a good linearity over the full operating range;

- the bandwidths of each element must correspond to the required *simulation frequency domain;*

- the delays introduced by these elements must be well known; the phase differences equivalent to these delays can be difficult to compensate and can generate RT simulation's instability;

- according to the foreseen applications, another essential characteristic that can be requested for the power amplifier is to be reversible, meaning that he must be able to generate as well as to absorb power.

Besides obtaining real current and voltages, the power interface scales the simulated models and the analogical part. The right gains must be introduced in order to have for example an 180 V analog converter connected to a 20kV digitally simulated grid [11].

3. HIL APPLICATIONS

3.1 Test of protection relays

The most common application of HIL simulation is the relay testing. As no large bench tests and no important short-circuit currents are present in the test facility, the HIL simulation is a safe testing method.

The RT HIL testing facility presented in Figure 9 consists in 'connecting' an analog protection relay to a digitally simulated network. The simulated network is made of a synchronous machine (SM) connected to an infinite bus via a step-up transformer and two 100km, 220kV, transmission lines. Circuit-breakers are placed at end of both lines.

One of the lines experiences a 3-phase fault, at the middle. The fault currents are measured, outputted via the digital-to-analog converters (D/A) and applied, as measured signals, to the protection relay. The relay is set to assure the over-current protection, so it analyses the current form and sends opening control signals, towards the circuit-breakers (via the digital inputs - DIn).

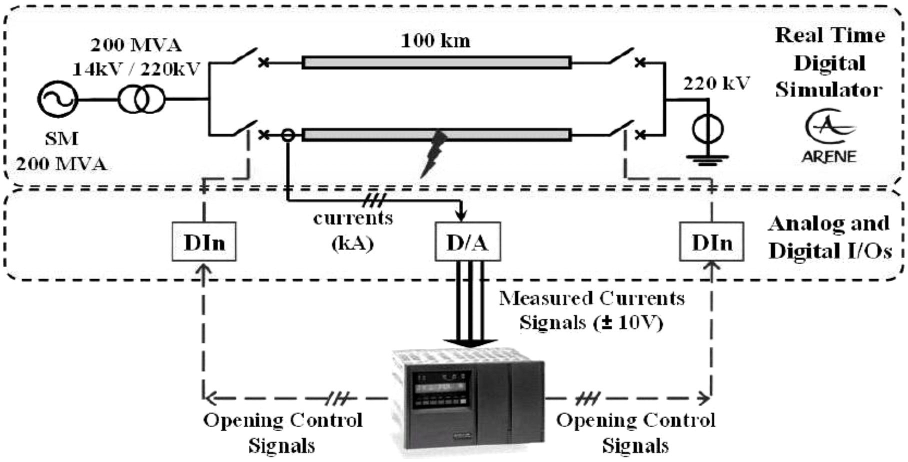

Fig. 9: Real-time relay testing facility

The detection capacity of the protection relay is therefore tested by simply changing the fault parameters into the simulated grid.

3.2 Test of a PWM controller

The benchmark presented on Fig. 10 allows the test of a D-STATCOM controller by using the RT HIL simulator. The application illustrates a possible solution to the case when the minimal simulation sampling time of the RT digital simulator is not adequate for acquisitioning a high frequency PWM signal. A hardware interface was therefore conceived [9].

The aim of the hardware interface is to extract the modulation signals of the PWM. It computes the averaged value of the PWM signals during a PWM period to extract the modulation signals.

Each simulation time-step, the RT digital simulator generates measurements from the simulation to the controller. The controller generates PWM signals (U) which are computed by the hardware interface to extract the modulation signals for the simulated D-STATCOM averaged model. Thus, a RT hardware-in-the-loop simulation is performed.

The D-STATCOM controller has been realized with a dSPACE system (RT simulator dedicated to controller prototyping) based on the Texas Instruments DSP TMS320C240 card. The controller algorithms have been implemented in the dSPACE and a sampling time of 120 µs has been chosen. The minimal simulation sampling time obtained with ARENE URT is 30 µs for the D-STATCOM and the power system simulation.

The benchmark was validated for the D-STATCOM PWM controller tests, with PWM frequencies in the range of 5 kHz up to 80 kHz. The results show that tests of industrial PWM controllers are now possible with the proposed method. For medium

PWM frequencies (1 kHz up to 10 kHz) another algorithm has been implemented in the hardware interface and validated successfully [12].

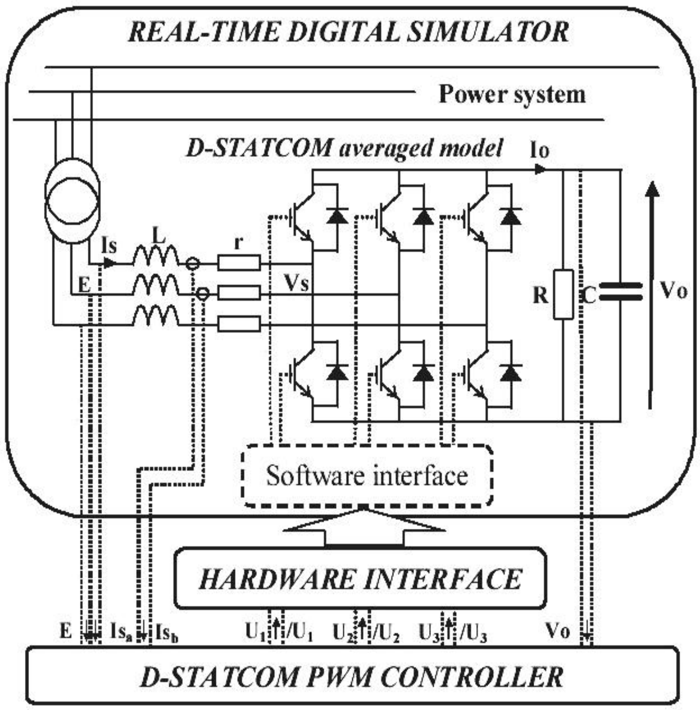

Fig. 10: Implementation of D-STATCOM PWM controller test using the RT simulator and the hardware interface

4. PHIL APPLICATIONS

4.1 Wind generation systems

Several studies have been carried out at G2Elab (Grenoble Electrical Engineering Laboratory) in the field of wind energy. Some of them were meant for the comparison of different generator types (DFASM – Double Fed Asynchronous Machine, SM – Synchronous Machine), studying their interaction with the grid. A second thematic, is the improvement of already existing wind farms, based on fixed speed machines, by the use of power electronics (DSTATCOM – Distribution STATic COMpensator, DVR – Dynamic Voltage Regulator), [11, 13].

As it fallows, there will be presented two of these applications.

4.1.1 DFASM wind turbine application

This application was carried out for the study of a DFASM wind generator. On the benchmark presented in Figure 11 there can be distinguished two distinct parts.

The first one is represented by the RT hybrid simulator, which comprises a RT digital simulator (ARENE URT) with its I/O boards, a power amplifier, a current sensor and an absorption resistor. The absorption resistor has the purpose to take in a part of the generated active power in order to not exceed the amplifier limits.

The second one, the wind generator's benchmark, contains a DFASM generator, and a direct-current machine (DCM) operating as a motor, modelling the wind turbine's behavior. The DFASM has the stator directly connected to the grid, while the rotor is connected via an AC/DC/AC interface (two IGBT based three phased voltage converters). Each one of the machines has its control system, which in the case of the DFASM permits to choose between different power strategies (maximum power point tracking –MPPT–, constant active power, etc.) while in the case of DCM it permits to modify the wind profile.

On the digital part, a 20 kV distribution network was modelled, including a voltage source (equivalent of the slack bus), 15 lines, 13 loads (0.4MW) and the controlled current source (equivalent of the wind generator). This configuration permits to perform simulation using a sampling time of 50 µs. Voltage drops and frequency variations are easily achievable by controlling the voltage source.

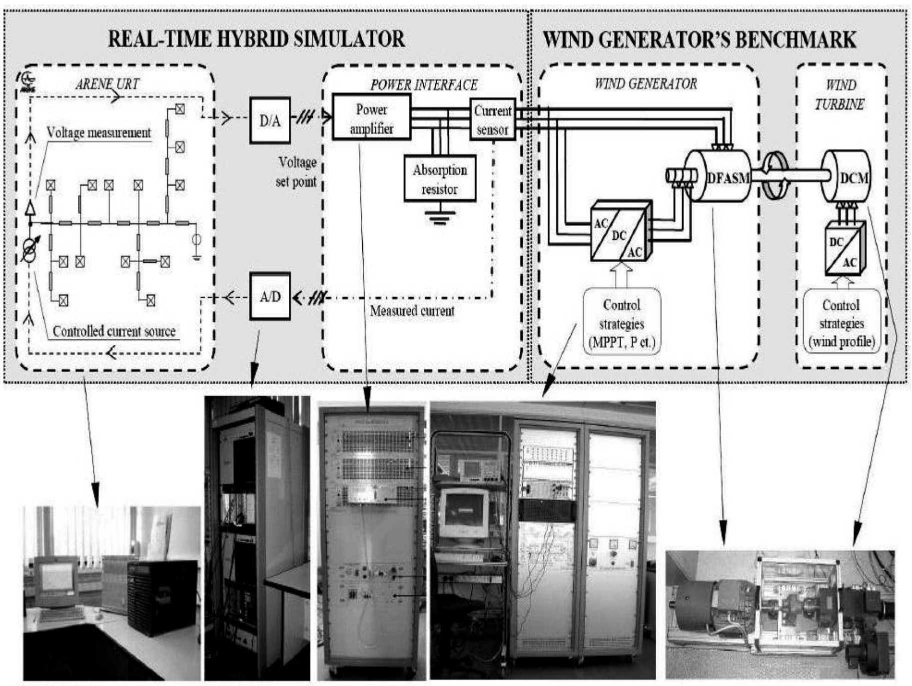

Fig. 11: Real-time PHIL simulation benchmark for DFASM wind turbine application

The utilized power amplifier has a rated output voltage of 180 V_{RMS}, a rated current of 40 A_{RMS}, respectively a rated power of 15 kVA and a bandwidth of 30 kHz. Due to the generator type, the power amplifier must be reversible in order to generate the reactive power necessary for the machine's magnetization and to absorb the power injected by the generator.

Concerning the wind generator, it operates at 140 V_{RMS} with a rated power of 7.5 kW, but due to the rated power of the DC motor (6 kW) and the power losses, the maximum active power injected is 3.7 kW.

Several tests were made to evaluate the hybrid system's behavior. The first set is realized in order to study the impact of the wind generator on the power grid. One group of experiments is made in variable wind conditions, keeping the grid's voltage and frequency constants. A second group consists in creating a 30 % voltage drop at the generator's connection point for a 20 s period. Therefore, this time it can be seen the response of the real wind generator face to power system's perturbations. The real (analogical) wind generator is tested by creating events on the digitally simulated grid.

4.1.2 Improvement of fixed-speed wind farms by using a reduced-scale STATCOM prototype

This application analyzes the contribution of power electronic compensators to the transient behavior of fixed-speed wind farms. The considered case study is a 36 MW wind farm composed of 40 squirrel cage induction generators with a rating of 0.989 MVA (0.9 MW). Each wind turbine is connected to the wind farm internal 20 kV cable network by a 1 MVA, 0.69/20 kV transformer. Power factor correction capacitors of 0.275 MVAr are connected at the low voltage terminals of each wind turbine generator. The wind farm is finally connected to the high voltage network by means of a 40 MVA, 20/220 kV transformer.

The wind farm is equipped with a D-STATCOM compensator and a capacitor bank. The capacitor bank provides the reactive power base demanded by the wind farm and the D-STATCOM is used for the compensation of the transients and the voltage oscillation damping. It is a 2-level D-STATCOM, based on series connected IGBTs. The considered switching frequency is 2 kHz. The reduced scale physical prototype used for RT emulation of the 20 kV and up to 50 MVA D-STATCOM is a 180 V converter rated in 2.5 kVA, [11]

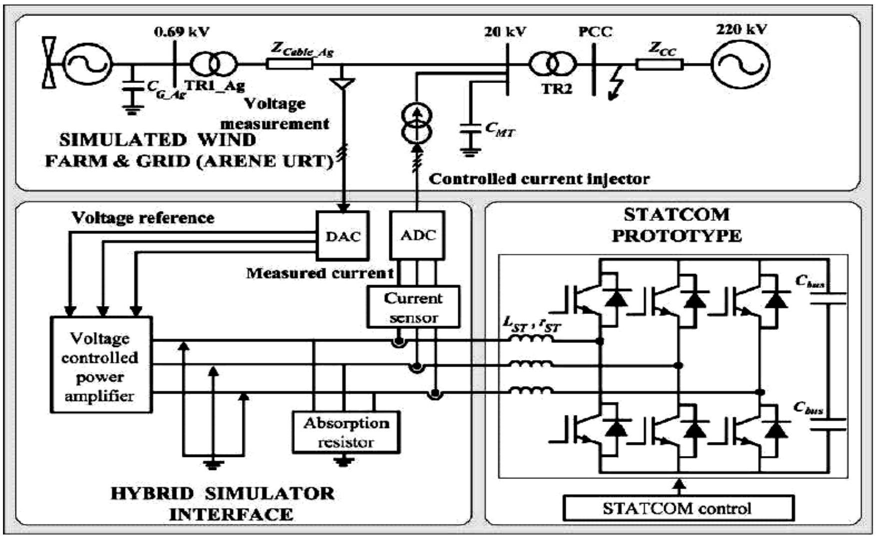

Fig. 11: RT PHIL simulation benchmark for D-STATCOM application

Critical aspects like STATCOM rating and control are analyzed in this application. The study highlights the great contribution of reactive power compensators to the transient behavior of fixed-speed wind farms and the importance of an appropriate control strategy choice on the performance and rating of the device.

Similar experiments were carried out concerning serial compensation systems (DVR) for the same wind farm, [13].

4.2 Photovoltaic generation systems

An experimental benchtest has been created at G2Elab in order to test real, industrial, PV inverters and to characterize their behaviors when they are connected to the network. The goal is to understand how each PV inverter detects the loss of mains and what are its performances and robustness. For the distribution network operator, the main concern is the potential disturbances created by the PV inverter and the islanding detection process. Besides, another interest is to evaluate the behavior of the PV inverter in the case of a sudden fall in the voltage.

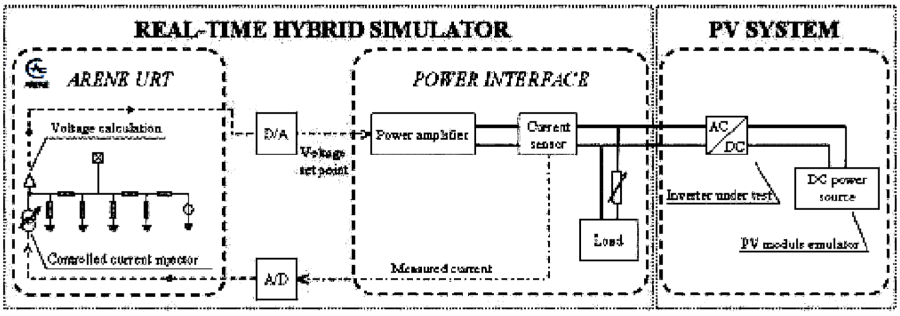

Fig. 12: RT PHIL simulation benchmark for PV invertors test

The digitally simulated network is deduced from data of existing low voltage distribution networks. It is composed of a perfect voltage source with a given short-circuit power, lines, loads and the exchange structures (the voltage measurement plus the controlled current source). By tuning the values of each element (lines, loads, switches status), it can be possible to create various cases to test how the inverter are compliant with DVE 0126.

The solar panels have been replaced by a DC programmable source. This generator will be controlled in order to emulate the behaviour of real PV panels. A load has been added near the PV inverter to test its impact on the performance of the anti-islanding method.

Various tests have been conducted with this benchtest and several PV inverters. The most common test is the impedance jump detection. The parameters that can be changed during the RT experiment are the following ones: *the impedance* seen by the inverter (before or/and after the connection), *the voltage* (magnitude of the voltage at the source) and *the frequency*.

This application has addressed the test of industrial PV inverters and their ability to fulfil the normative requirements regarding VDE 0126. [14]

5. CONCLUSION

It can be concluded that the realized benchmark permits to observe the behavior of renewable generation system as in real operating conditions, as connected to a real power grid. It is possible to study both, the impact of the production system on the power system as well as the impact of the power system's perturbations on the production system.

The present paper has also shown that the Real-Time Hybrid simulation (Hardware-In-the-Loop and Power-Hardware-In-the-Loop) are the perfect ways to test industrial devices close to their real functioning conditions. The conceived test facility shows even more its advantage, as the devices into test are “enclosed” and they must be considered as black-boxes in order to study their comportment.

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