# Real-time simulation: the missing link in the design process of advanced grid equipment

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***Abstract*--This paper describes a design process of advanced grid equipment including both dynamic simulations and power-hardware-in-the-loop. A case study concerning the insertion of an energy storage system in a large isolated grid is used as an illustrative example. First, the methodology developed to achieve a real-time simulation of the studied grid from its original dynamic model is presented. The real-time platform used within the framework of this project is based on the RT-LAB environment and is interfaced with real ultracapacitors through a power amplifier. Some experimental results are analyzed in the final part. The advantages of this methodology including power-hardware-in-the-loop are emphasized by illustrating its contribution to dynamic model validation and the obtained improvement in control system performances.**

***Index Terms*—design process, distributed generation, energy storage systems, isolated power grids, power-hardware-in-the-loop, real-time simulation, ultracapacitors.**

## I. Introduction

THE real-time simulator performances are following the evolution in computer technologies and can provide designers with an efficient approach to system prototyping and testing using “Power-Hardware-In-the-Loop” (PHIL) digital simulation. PHIL enables the test of advanced, real devices, such as Distributed Energy Storage Systems (DESS) or Distributed Generation (DG), by connecting them to a grid model that is simulated in real time [1]. This way, the studied equipment behaves as if it was connected to the real network: it can thus be tested over a wide range of grid configurations, including fault conditions, without any risk.

In recent years, PHIL gave promising results within the framework of research projects dealing for example with wind energy conversion system [2], gas micro-turbine integration in distribution networks [3] or small-scale distributed generation (DG) systems [4]. However, the existing work deals usually with micro-grids and the potential of hardware-in-the-loop simulations for large scale isolated grids should now be studied, since they are expected to accommodate more DG and other advanced grid equipment in the years to come.

Isolated power systems have specific features compared with large interconnected grids, such as significant dependence on oil generation plants, leading to higher production costs and emissions, and lesser sturdiness to electrical disturbances resulting in frequent voltage/frequency fluctuations and power quality concerns. Besides, the variability brought by renewable-energy based DG and its current lack of contribution to ancillary services can impact weak grids operation and stability. That is why island grids are said to have a strong potential regarding the development of DESS for various applications. Non real-time modeling and simulation have traditionally been used for carrying out studies on this topic, as shown in [5] (dynamic simulations of a 30MW battery providing frequency regulation to the Israeli isolated grid), [6][7] (dynamic simulation and experimentation of a flywheel energy storage system in Azores) and [8] (step by step sizing of solar/storage systems for Greek islands).

The purpose of the present paper is to illustrate, through the example of an innovative application of DESS on an island grid, how it is possible to move from a classical design approach to a “real-time” process and to discuss the benefits gained from this switch. The main difficulty of the real-time simulation of a large scale isolated grid is related to the complexity of the grid’s structure and of the synchronous machine model. Hence, by simulating the complete network in a single processor of the real-time simulator, it was found that the required computation time was far beyond the maximum time-step to achieve real-time simulation. Work was therefore conducted to propose and validate solutions permitting either to distribute calculations in several cores or to simplify the network by reducing the number of simulated generators.

In the following sections, the objectives of the illustrative case study, which concerns the implementation of an ultracapacitor-based DESS in Guadeloupe island are first presented, as well as the main characteristics of the grid. At first, the study was conducted by using usual dynamic simulations and the results were then experimentally validated with a small-scale, real storage system. The process leading to experimental validation and the solutions to enable real-time simulation of the Guadeloupe power grid are then described. The last part of the paper focuses on the contribution of PHIL

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to the design process of advanced grid equipment.

## II. From Dynamic Simulations to Experimental Validation Through Hardware-in-the-Loop

Because of frequent tripping of generators or grid disturbances such as short-circuits and the lack of interconnection in island networks, load-shedding is often requested to restore the balance between production and consumption in these incident situations. An innovative DESS application is used herein to illustrate the possible design process improvements with PHIL. The result of a study involving grid operators (see [9] for details) have highlighted a great interest in the use of ultracapacitors to help maintain the frequency of an island network within admissible limits after a generator tripping. The participation of DESS to frequency regulation consists in injecting active power when the frequency drops below 50Hz or absorbing active power in the opposite situation, which can reduce the annual outage time.

### *A. Brief Description of the Case Study*

In agreement with the integrated system operator of French isolated energy systems (EDF SEI), the use of distributed storage for frequency control was studied on the case of the electrically isolated archipelago of Guadeloupe. Located in the eastern Caribbean Sea, this overseas department of France comprises five islands: Basse-Terre (848 km$^2$), Grande-Terre (588 km$^2$, separated from Basse-Terre by a narrow sea channel) and the adjacent islands of La Désirade, Les Saintes and Marie-Galante. Guadeloupe covers about 1,600 square kilometers and its population was 407,000 inhabitants in 2008.

The peak power consumption of the network reached 242 MW in 2007 [10]. Fig. 1 shows the major production centers of the island and the structure of its HV transmission grid.

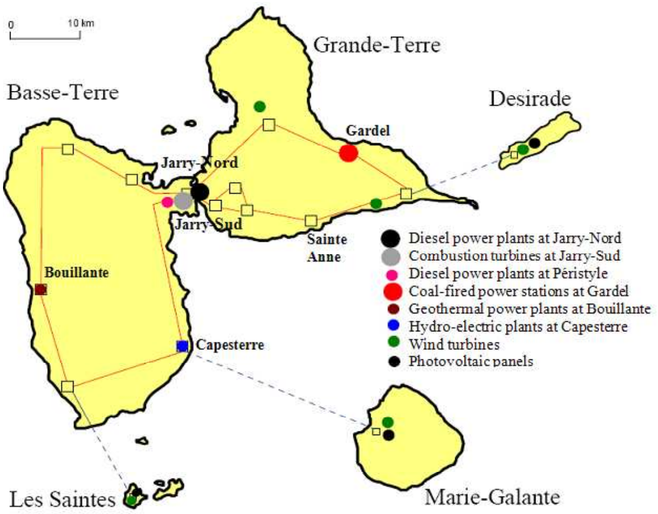


Fig. 1. HV grid, major generation plants and DG location in Guadeloupe

The transmission system is operated at 63 kV and includes 13 substations. Each substation consists of 2 step-down 63/21kV transformers with on-load tap changers to adjust the voltage on downstream distribution grids.

The installed generation at the end of 2008 consists of eight 21 MW diesel power plants at “Jarry-Nord” substation and two 32 MW coal-fired power stations at “Gardel” substation participating in primary frequency control. Three smaller diesel groups (5 MW) at “Jarry-Sud” substation, distributed hydro-electric plants (9,6MW) as well as geothermal power plants (5+10 MW) at “Bouillante” substation are often operated at their rated power. Four combustion turbines at “Jarry-Sud” substation are solicited only during peak demand (3x20+40 MW). Wind (26.4 MW) and solar (5 MWp) based power sources have been connected over the past few years but their shares in the annual energy mix remain rather marginal, with respectively 2.59 % and 0.16 % in 2006.

Several configurations of the network were taken into account to assess the potential of ultracapacitor-based DESS for frequency support. The various simulated incidents included the tripping of a coal-fired generator producing around 25 MW during off-peak situation (140 MW), with minimal power system inertia. Due to the relatively slow response of diesel plants while delivering their primary reserve, the grid frequency drops quickly below the load-shedding threshold in such a situation. An outage is therefore experienced by customers even if the primary reserve on remaining power plants is sufficient from a static point of view. DESS modeled as power or current injectors were connected at distribution levels in the simulated Guadeloupe power system. A specific control algorithm was developed so that DESS may dynamically assist the real power injection following generator tripping.

The present document focuses on the contribution of PHIL simulation in the design process of innovative grid equipment and uses this case study as an illustrative example. The detailed results of the study presented above, including DESS sizing, impact analysis and cost/benefit assessment will be published soon in a dedicated paper.

### *B. Simulation results obtained with Eurostag software*

The development of the required, innovative control algorithm and the first characterization of the use of distributed storage for frequency support in large isolated grids were carried out using Eurostag commercial software. Eurostag is a time-domain simulation program that is utilized at EDF R&D for dynamic studies of isolated French grids [11]. It uses phasor representation for power system dynamic simulation (transient, mid and long-term stability). Thanks to its variable step size integration method, fast simulation of a large set of configurations was possible to ensure a complete analysis of the Guadeloupe case study, including a wide range of DESS nominal power values as illustrated in Fig. 2.

Through dynamic simulations, a first tuning of the control system for storage frequency control was proposed. A significant impact of ultracapacitors on frequency excursions following generation tripping was demonstrated, leading to the decision to pursue further investigations on this topic.

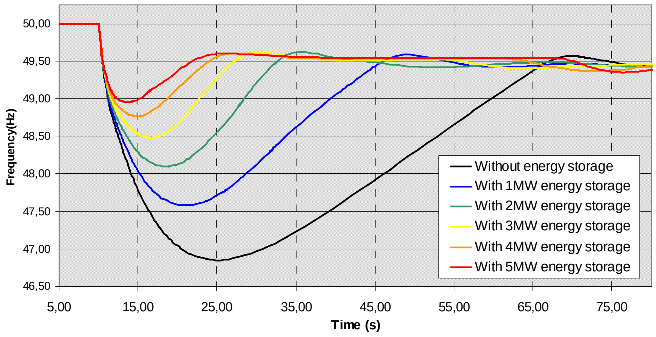


Fig. 2. Impact of ultracapacitor-based DESS on the frequency response of an isolated power system after a major generation loss

## *C. From Dynamic to Real-Time Simulation*

In order to validate simulation results and the robustness of the designed control system, the Guadeloupe power system has been simulated on the real-time simulation software environment RT-LAB (core of the PHIL platform currently under development at L2EP) with real ultracapacitors. Opal-RT RT-LAB allows the user to convert Matlab Simulink models, and then to run real-time simulations of those models on multiple target computers equipped with multi-core PC processors. This is used particularly for PHIL and rapid control prototyping applications [12].

As Eurostag files cannot be compiled directly on RT-LAB the Guadeloupe network model has to be transposed into Matlab Simulink and SimPowerSystems (SPS) models. We used SPS library blocks to simulate basic elements of the grid, such as "Standard Synchronous Machine" or "Pi Section Line". Control systems and processes (power plants AVR, speed governors, etc.) were modeled using Simulink blocks.

Simulation results obtained with Eurostag were compared with those obtained with SPS under phasor mode with a variable step size. In this computation mode, only complex forms but not sinusoidal forms of voltage/currents are treated for calculations. The dynamic behavior of the Guadeloupe power system on the two different pieces of software was found to be in very good agreement. Static errors were typically far less than 1%, which validated the grid model conversion from Eurostag to SPS. The phasor representation is of standard use for stability problems. However, as it implies quasi steady-state, information inside the cycle is partially lost.

The Guadeloupe grid model was then simulated under SPS discrete mode with a 50µs fixed step-size, which is the maximal time-step ensuring satisfactory convergence of the simulation due to the power system complexity. The ARTEMIS solver from Opal-RT Technologies was utilized in order to optimize SPS power systems' simulation in discrete mode. It is a fundamental constraint of real-time simulation that the model must use fixed-step integration solvers. ARTEMIS introduces fixed-step solvers improving the performances of SPS and enables real-time simulation of complex power systems.

## *D. Real-Time Simulation Using RT-LAB Environment*

The complexity of the Guadeloupe power system requires much computational resources to be simulated in real-time (meshed network with up to a dozen of generation plants). When simulating the complete grid in a single processor of the real-time simulator, the corresponding computation time for the original model greatly exceeded the maximum admissible computing time-step of 50µs. It was therefore not guaranteed that the studied grid would be simulated in real time: possible overruns would have caused communication problems as real equipment was interfaced to the simulator. To meet real-time requirements, some solutions were tested either to distribute calculations in several processors or to simplify the grid structure (and associated set of equations) by reducing the number of synchronous machines.

### *1) Multi-core computing of Guadeloupe grid model*

The distributed configuration enables the distribution of complex models over a cluster of multi-core PCs running in parallel, thus reducing computation time to achieve real-time performances. The target nodes in the cluster communicate between each other with low latency protocols and the real-time cluster is linked to a RT-LAB command station (Fig. 3) through a TCP/IP network.

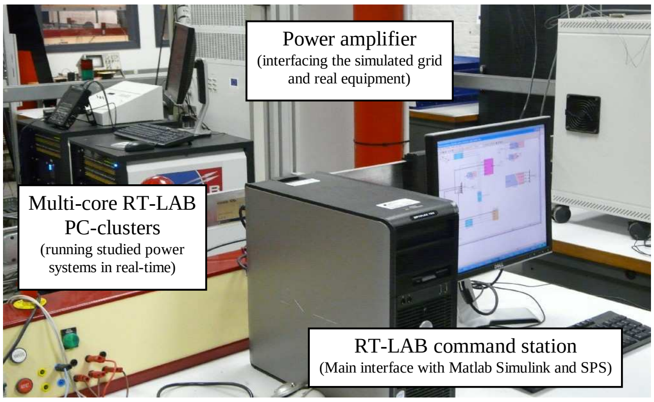


Fig. 3. RT-LAB PC-cluster targets and command station at L2EP hardware-in-the-loop experimental facility.

Parallel distributed solving implies a separation of the studied power system and the allocation of the subsystems to different cores of the target PC-clusters, each one being solved by a unique core. In RT-LAB environment, this operation is achieved through the use of two blocks from ARTEMIS library, which are respectively the "distributed parameter line" and the "stubline". Their function is to decouple the grid in discrete mode to reduce system's matrix state that is processed by each core during calculations.

"Distributed parameter lines" are utilized to replace some transmission Pi-section lines in order to separate the grid for multi-core computing. With these blocks, a 1-time-step delay (corresponding to the actual propagation delay of the transmission line) is introduced in the simulation so that information can be shared between the calculated subsystems.

To ensure simulation accuracy and stability, the propagation time in the considered lines must be higher than the simulation sampling time. For a 50 Hz network with a 50µs time-step, a 63kV transmission line cannot be replaced by a "distributed parameter line" for parallel solving unless it is longer than 15km. Therefore, with the considered Guadeloupe grid has been separated this way into three subsystems: "Grande Terre", "Basse Terre" and the main generation center "Jarry-Nord"/"Jarry-Sud" (see Fig. 1).

"Stublines" are short decoupling lines that add artificially a propagation time equal to a single time-step. They were utilized to replace the primary windings of some HV/MV transformers of Guadeloupe. Several grid's substations were separated this way at their step-down transformers and affected to an additional core of the PC-cluster.

Finally, with the two essential decoupling elements of the ARTEMIS library, parallel distributed solving of Guadeloupe grid equations was realized across 4 duo core GHz processors.

#### 2) *Model simplification*

The complexity of the synchronous machine model limits the number of generation plants that can be processed by a single core to achieve real-time performances. According to our experience, this number is restricted to 3, which can be insufficient depending on the characteristics of the power system to be simulated: for example, in Guadeloupe, 8 diesel generators are connected to the 63kV "Jarry-Nord" busbar.

Since the electrical distance is small in the Jarry Nord power plant, it was possible to group these synchronous machines with same characteristics and identical operating point by keeping per-unit parameters and scaling up the nominal power of the resulting aggregated power plant model to the total one of the generators grouped together.

#### 3) *Simulation results*

Tripping of various generators were simulated using RT-LAB. Fig. 4 shows the frequency responses of the Guadeloupe power system after a major generation loss on the three pieces of software: Eurostag (dynamic simulation software), SPS (intermediate software) and RT-LAB (real-time environment). This comparison allows us to validate the real-time simulation of the grid model, as the results are in good agreement.

The slight deviations that appear in the recorded responses (minimal frequency and lag) can be explained by differences in the load modeling approach between Eurostag and SPS, and by the above-mentioned required operations to achieve real-time performance. Nevertheless, this difference does not impact significantly the DESS experimental test.

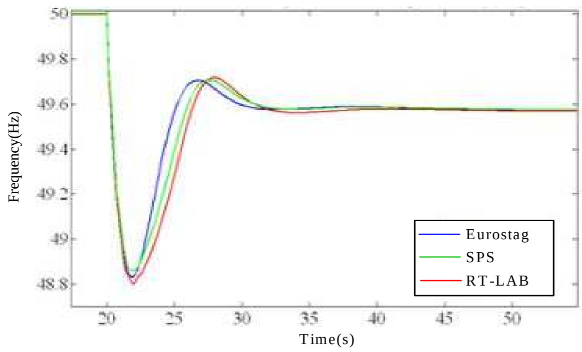


Fig. 4. Comparison of the frequency responses of the various Guadeloupe power system representations during a similar generation loss scenario

### *E. Experimental set-up at L2EP PHIL platform.*

To perform experimental validation of the developed DESS models and of their control systems, the simulated storage system was finally replaced by real ultracapacitors. To this end, the Guadeloupe power system model was simulated on the real-time simulator. The voltage at the MV side of "Sainte Anne" substation (location of the studied DESS) was measured every 50µs (sampling time of the real-time simulation) and sent to an analogical output of the simulator. After reducing the voltage values by a gain *Gv*, the voltage information was sent to a three-phase bidirectional power amplifier as shown in Fig. 5. This voltage was thus generated and powered the 400V busbar of the experimental platform, where the real ultracapacitor-based storage system was connected.

The real energy storage unit comprises four Maxwell 165F BMOD0165-P048 modules connected in series and a dedicated power electronic conversion system including a PWM boost chopper and a 5kW PWM inverter. The DESS supervision, built in a DSP dSPACE card, allows controlling the injected current through the inverter and the level of DC bus voltage through the chopper (Fig. 6).

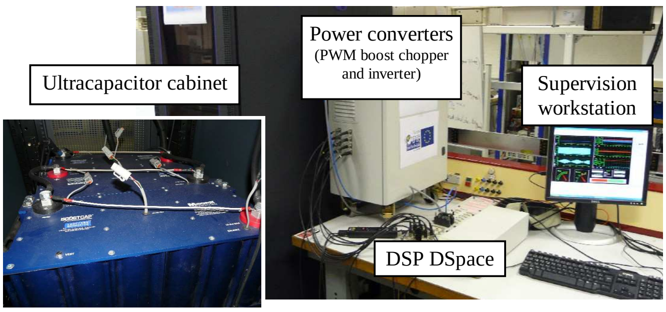


Fig. 6. Experimental 5kW/40F ultracapacitor-based storage system

A current adaptation has also been performed by using a second gain *Gi*, by which the return current signals from the real DESS is amplified. In this way, a 5kW injection from the real energy storage unit to the amplifier is taken into account as if it was 3.5MW for the real-time simulation.

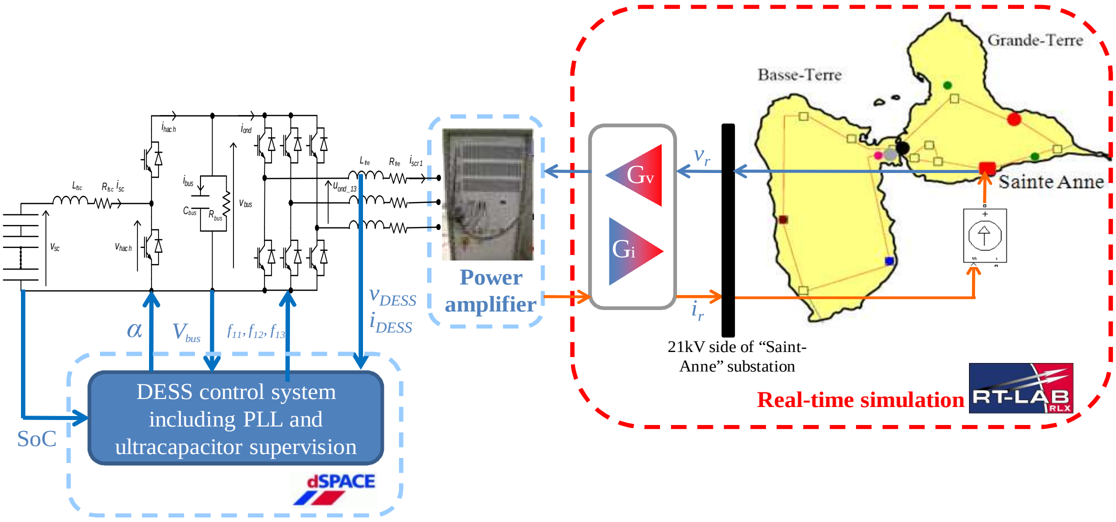


Fig. 5. Presentation of the PHIL experimental platform at L2EP

## III. Improving Usual Dynamic Studies And Control Design Using Real-Time Simulation

In this last section, the contribution of PHIL simulation within the design process of an innovative grid concept is studied. The case study of DESS for frequency support in Guadeloupe island grid is used as an illustrative example.

### A. Improvement of the Control System Performances

A major interest of PHIL has been its contribution to the improvements of the DESS control algorithm. As explained above, the first version of the control system of the studied DESS was developed and tested by using dynamic simulations, with satisfactory outcome compared with the specifications. Thanks to results obtained using Eurostag software, preliminary system sizing, impact analysis and cost/benefit assessment demonstrated the possible interest of the studied DESS application and led to the decision to proceed with small-scale testing through real-time simulation.

As the control system was being phased in at L2EP PHIL platform, many adjustments were necessary to make it operational: notably soft-start sequence, emergency stop command and improvements of the control algorithm to account for non-ideal behavior of real equipment and sensor noise. To illustrate this point, the following paragraphs focus on the DESS synchronization, which was one of the modeling problems identified thanks to real-time simulation.

To ensure fast active power injection after a major generation loss, the developed DESS control system was partly based on the frequency decline gradient. The usual power and current injectors available in dynamic simulation software for fast modeling of distributed power sources do not take into account inverter synchronization control: that is why the signal used for inverter reference calculation in the first version of the control system was the grid frequency (through ideal measurement block). Following a significant generator tripping, the frequency decline gradient threshold was therefore immediately reached, leading to instantaneous start of DESS active power injection.

Experimental results with the real ultracapacitor unit showed that the transient behavior of the phase locked loop (PLL) must be taken into account as it delays significantly the detection of the frequency decay by the DESS (and therefore, impacts the active power reference calculation). Indeed, in practice, the frequency estimation made by the inverter control synchronization apparatus derives from a measurement of the instantaneous grid voltage at the DESS connection point. Therefore, disturbances of the measured voltage have a significant impact on the frequency estimation done by the PLL. This phenomenon, which was not taken into account in the first dynamic simulations, is illustrated in Fig. 7: transient errors in the frequency estimation appear following the voltage variations related to generator tripping (a) or DESS active power injection (b).

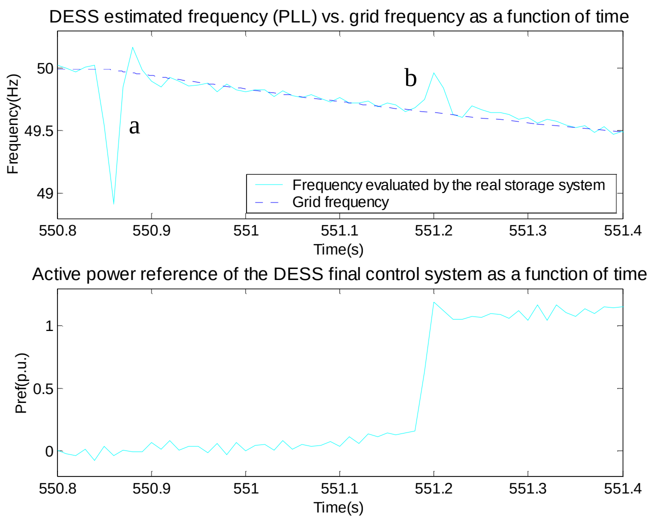


Fig.7. Measured and grid frequency after major generator tripping.

Adapted filtering and delays were added in the experimental control system to ensure a proper detection of fast frequency decreases and high immunity to measurement noise and to fast voltage variations at the connection point. Since they increased the response time of the studied storage system of a few 100 ms on large generator tripping situations (because of the filtering effect, Fig. 7), these necessary changes were likely to impact the initial dynamic simulation results. The control system implemented on Eurostag software was therefore updated to consider lessons learnt from PHIL and the conclusions of the preliminary dynamic studies were slightly refined with a more realistic DESS behavior.

### *B. Feasibility Demonstration and Model Validation*

Another great interest of power-hardware-in-the-loop simulation is the possible fast experimental implementation of the developed concepts.

In some references, such as the flywheel energy storage system case presented in [6] and [7], dynamic model validation is done using real measurements on a full-scale (350kW/5kWh) pilot facility in Azores. As complete and interesting such an iterative process using a full-scale field experiment can be, it is however limited to particular situations such as isolated grids and hardly applicable in general. In addition of obvious economic and safety reasons, the connection process of grid equipment is usually time-consuming, particularly when innovative concepts and technologies are concerned. For example, special factory and site acceptance tests in accordance with existing standards, permitting and/or complementary engineering work when a unique design is required can lead to considerable delays and additional costs. Lessons learned from the installation of new energy storage systems in distribution grids over the past few years have illustrated these kinds of difficulties, as in [13]. The financial risk for utilities is significant: e.g. millions were lost when large-scale “Regenesys” demonstration plants were cancelled at an advanced stage of their building [14][15].

Real-time simulation is a convenient intermediary step between usual dynamic simulation and full-scale experimentation of innovative power-system concepts: it enables fast prototyping and testing of new grid equipment under the various operation conditions it can possibly encounter during its service life, including fault conditions. This way, with moderate expense and time, substantial conclusions can be drawn regarding:

*1) The practical feasibility and safety of the tested concepts*

By using PHIL, it becomes possible to re-create in the laboratory the electrical constraints that a given device will face at commercial stage: frequency or voltage slow/transient deviations at the connection point, changes in the controlled variable(s), etc. It can thus be verified whether or not a given concept is technically feasible with the available technologies and capable of safe grid-connected operation (disturbances generated on the grid, fault ride-though performances, etc.). Moreover, the compliance of the tested device with the requirements of the grid code can be checked as well.

As far as power systems are concerned, it is most likely that the feasibility demonstration will be carried out at a reduced scale. Providing that the change of scale is proven to be possible, the results will still remain of great interest in the decision making process possibly finally leading, with reduced risks, to a later large-scale experimentation.

Fig. 8a and 8b show the frequency measurement (phase locked loop output) and the active power injection by the real 5kW DESS after a unit generation trip on the simulated Guadeloupe power grid. Up to now, stable charge/discharge cycles and standby operation were demonstrated over long PHIL sequences (up to 1 hour) including generation loss and reconnection with subsequent frequency and voltage variations at connection point (including voltage dips).

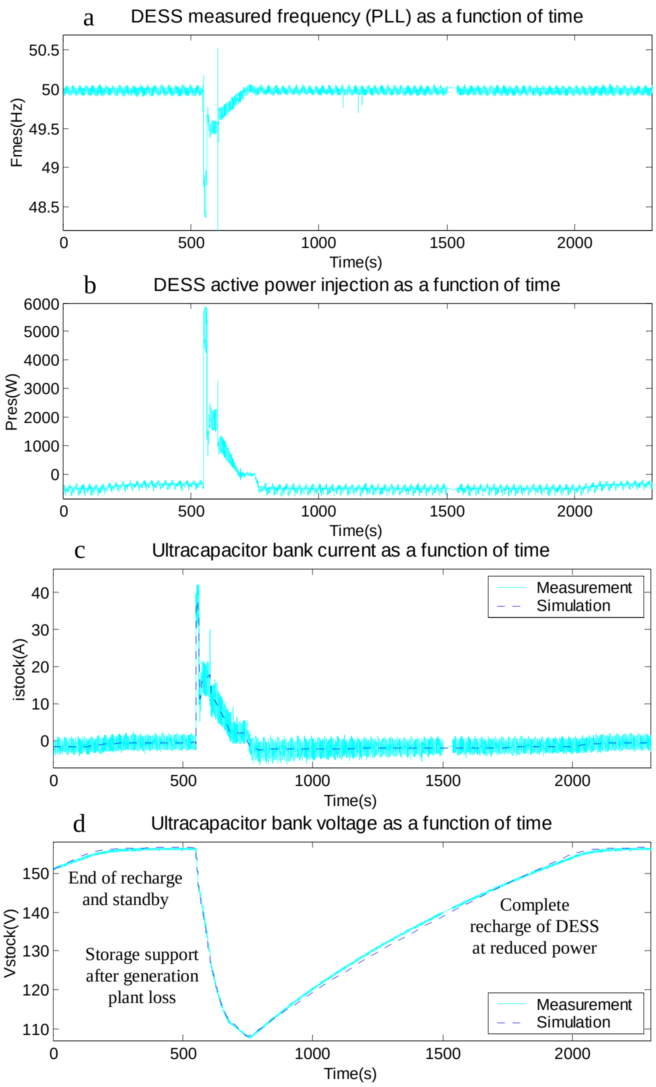


Fig.8. DESS PLL frequency estimation (a), active power injection (b), ultracapacitor bank current (c) and voltage (d) as a function of time.

*2) The validity of the models used for dynamic simulations*

Thanks to fast experimental implementation of the studied DESS, PHIL simulation made possible a complete validation of the models used for dynamic simulations. To this end, measurements on the real unit and model responses during typical charge/discharge/standby cycles were compared. For all the considered working conditions, the results were found to be in good agreement. For instance, Fig. 8c and 8d show real vs. simulated voltage and current of the 40F ultracapacitor bank over a generator tripping situation. A new loss model to calculate the AC round trip efficiency of grid-connected storage systems was also successfully tested.

### *C. The Real-Time Improved Design Process.*

Finally, PHIL was particularly helpful to improve the realism of the developed control system far beyond what could have been done using only dynamic simulations. In fact, these two tools were found to be rather complementary: the improved DESS model developed after PHIL was then extensively utilized for fast, long-term simulation of various configurations with Eurostag. This process resulted in a complete characterization of the studied storage application including experimental validation of key elements.

As a summary of the various points discussed above, the following Fig. 9. compares a “classical” design process of innovative grid concepts and a new, improved method using real-time simulation, with some of the identified advantages.

## IV. Conclusion

Based on the experience of a case study concerning the use of energy storage systems for frequency support in large isolated power system, a new design process of advanced grid equipment was investigated in the present paper. Classical dynamic simulations of energy storage systems connected to the Guadeloupe network model were first used for preliminary investigations. Since these results appeared to be promising, it was decided to proceed with small-scale experimental test through hardware-in-the-loop. The control algorithm developed with Eurostag was implanted on a real 5kW/40F ultracapacitor-base storage unit connected to the simulated grid running on RT-LAB environment through a reversible power amplifier. In this way, it has been possible with minimum delay (a few months) to demonstrate the feasibility of the developed concepts, to validate the dynamic models of the storage system and to improve its supervision algorithm so as to achieve successful, safe grid-connected operation of the tested ultracapacitor-based energy storage unit.

Dynamic simulations and hardware-in-the-loop were used as complementary tools to provide the grid operator with a complete characterization including refined system sizing, impact analysis, cost/benefit assessment, operational control algorithm and experimental validation of key points.

## V. Acknowledgment

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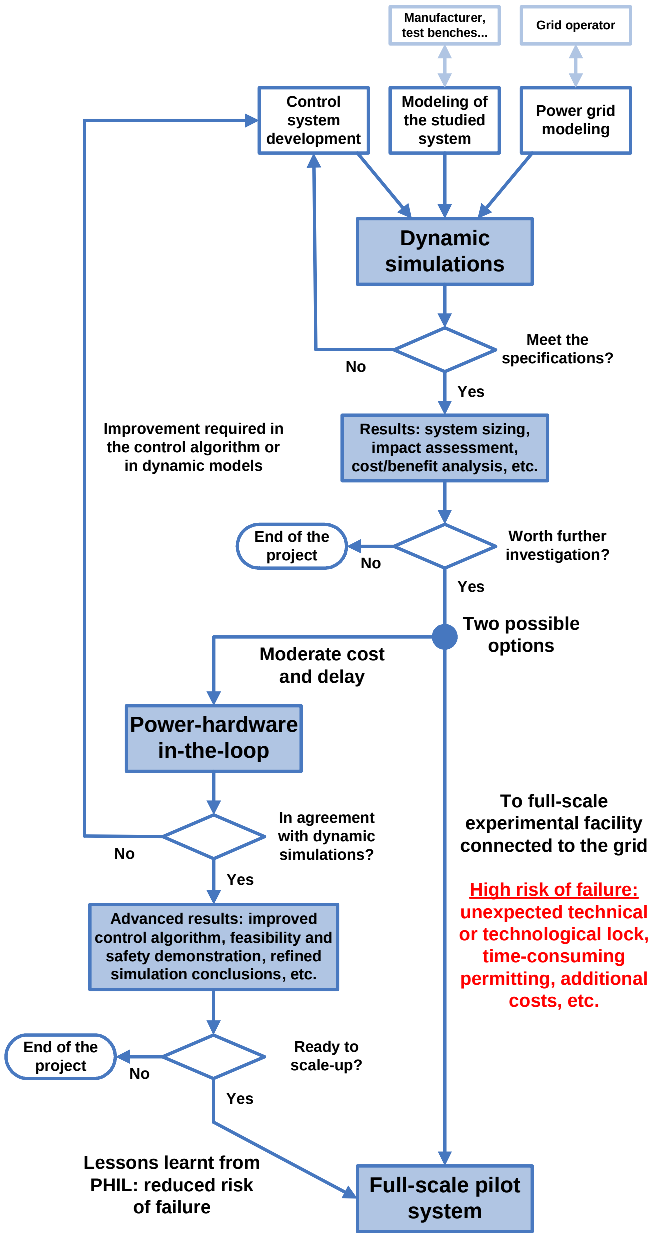


Fig.9. An improved design process including power-hardware-in-the-loop

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# VII. Biographies


**Ye Wang** was born in Nanjing, China, on May 03, 1986. He graduated in multi-disciplinary engineering from Ecole Centrale de Lille (France) and received a second Master’s degree in “Electrical Energy and Sustainable Development” from the University of Lille in 2009.

His field of interest includes power system analysis, real-time simulation and wind energy integration analysis. Currently, he is a PhD student funded by the French Agency for the Environment and Energy Management (ADEME) and EDF R&D.

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**Gauthier Delille** was born in Lens, France, on March 23, 1984. He graduated in multi-disciplinary engineering from Ecole Centrale de Lille (France) and received a second Master’s degree in “Electrical Energy and Sustainable Development” from the University of Lille in 2007.

His field of interest includes power system analysis, distribution grids and distributed energy storage systems. At present, he is a PhD student, working closely together with EDF R&D and the French Agency for the Environment and Energy Management (ADEME).

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**Xavier Guillaud** (M’2004) received a PhD in electrical engineering in 1992 from the University of Science and Technology of Lille (USTL), France. He joined the Laboratory of Electrical Engineering and Power Electronics of Lille (L2EP) in 1993.

His field of interest includes the modelling and the control of power electronic systems. Since 2001, he has also been working on the integration of dispersed generation in electrical grids.

Xavier Guillaud is a Professor at the department of Electrical Engineering of Ecole Centrale de Lille, Cité Scientifique, BP 48, 59651 Villeneuve d'Ascq Cedex, France.



**Frédéric Colas** was born in Lille, France, on October 17, 1980. He received a PhD in control system in 2007 from Ecole Centrale de Lille (France). He joined the Laboratory of Electrical Engineering and Power Electronic of Lille (L2EP) in 2008.

His field of interest includes the integration of dispersed generation systems in electrical grids and hardware-in-the-loop simulation.

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**Bruno François** (M’1996, SM’2006) was born in Saint-Amand-les-Eaux, France, on January 19, 1969. He received the PhD degree in electrical engineering in 1996 from the University of Science and Technology of Lille (USTL), France.

His field of interest includes power electronics, renewable energy sources and power systems. He is currently working on renewable energy based active generators and on the design of advanced energy management systems.

Bruno François is with the Laboratory of Electrical Engineering and Power Electronics of Lille (L2EP) and is an Associate Professor at the department of Electrical Engineering of Ecole Centrale de Lille, Cité Scientifique, BP 48, 59651 Villeneuve d'Ascq Cedex, France.