Accelerated-time and reduced-scale Hardware-In-the-Loop tests of an islanded microgrid

Anthony Roy, Florian Dupriez-Robin, François Auger, Salvy Bourguet, Quoc Tuan Tran

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Anthony Roy
IREENA
Université de Nantes
Saint Nazaire, France
anthony.roy1@univ-nantes.fr

Florian Dupriez-Robin
CEA Tech Pays de Loire
CEA
Bouguenais, France
florian.dupriez-robin@cea.fr

François Auger
IREENA
Université de Nantes
Saint Nazaire, France
francois.auger@univ-nantes.fr

Salvy Bourguet
IREENA
Université de Nantes
Saint Nazaire, France
salvy.bourguet@univ-nantes.fr

Quoc Tuan Tran
LITEN
CEA
Le Bourget du Lac, France
quoctuan.tran@cea.fr

***Abstract* — The optimal sizing, the energy management and the control of microgrids face to technical and economical constraints. Thus, simulation and tests at reduced scale must be carried out before a real implementation. So as to ensure that the energy management system and the control strategies are reliable and correspond to the network requirements, the microgrid components must be scaled to make the experimental tests with laboratory devices possible. The state of the art show that the size scaling is often considered for the validation of microgrid control, but the accelerated-time aspect is not included. Thus, it is proposed in this paper a combined size and time scaling method in order to propose size-scaled and accelerated-time Hardware-In-the-Loop experiments. This method, which is based on a dimensional analysis, allows the dynamics of the islanded microgrid model to be kept, while reducing the experiments time. The scaling method is firstly validated in simulation, before applying it on an experimental test bench. The renewable sources and the load are simulated in real-time, whereas a reduced scale battery is used. The obtained results allow the control of microgrids to be validated at reduced scale while reducing the experiments time.**

Keywords — Hardware-In-the-Loop, Microgrid, Scaled system, Time acceleration, Battery testing.

I. Introduction

The use of renewable energy sources and storage solutions in island areas is more and more considered in order to replace fossil energy sources [1], [2]. However, some technical constraints exist such as the variability of these resources and their ability to ensure the demand to be met. Moreover, the cost of some renewable energy sources, such as ocean energy sources, and the cost of storage solutions are still high [3], which does not ease the integration of such solutions in islanded grids. Thus, the microgrids based on the use of renewable energy sources and energy storage means must be designed carefully to avoid reliability and economic issues. This implies that the microgrid operation must be validated before its full-scale development, which is done firstly by simulation then by considering the use of physical devices at a reduced or a full scale. A lot of papers dealing with Hardware-In-the-Loop (HIL) simulation exist in the literature [4], [5]. The main advantages are related to the cost saving, as the risks related to the full-scale deployment are reduced. However, the full-scale devices often have a power range outside that of experimental laboratory test benches. Thus, reduced-size devices are often considered in HIL tests, but scaling is not always taken into account [6]. Moreover, the reliability requirement of microgrids needs to take into account a long test period and different cases of operation, to include critical situations, which could be a time consuming process. Thus, the microgrid design could benefit from accelerated-time tests, allowing development costs saving.

So as to carry out accelerated-time tests while considering the HIL aspect and without modifying the dynamics of the system, the scaling must be done carefully. A lot of papers deal with size scaling, especially for transport applications where the HIL tests are often carried out [7], [8]. The considered methods are often based on a dimensional analysis and the similitude theory, allowing the behavior of the system to be kept at a full scale and at a reduced scale [9]. However, a time scaling combined to a size scaling for HIL experiments is still scarce in the literature. For example J. Cabello *et al.* proposed in [10] a scaling method based on a dimensional analysis, in order to carry out reduced scale and accelerated-time HIL tests of a real battery. A. Varais *et al.* considered in [11] a similar method, applied to a wind turbine model and validated on physical emulators. In [12], only a size scaling for a battery is considered to make HIL experiments at a laboratory scale. However, the state of the art shows that there is no study dealing with accelerated-time and reduced-size scaling for microgrid control. So as to be able to validate microgrid control algorithms at reduced scale, a method must be proposed to ensure the dynamics of the system to remain unchanged and the correct decisions to be applied in time.

This paper proposes to apply a scaling method on an islanded microgrid, in order to carry out HIL tests with a reduced scale battery while considering accelerated-time experiments. The aim of the paper is to validate the ability of an energy management system (EMS), designed for a full scale microgrid, to correctly manage a microgrid at reduced scale in presence of a real battery. This paper is organized as follows: in Section II, the scaling method proposed for the model of the microgrid is presented. Then, the scaling method is validated in simulation in Section III thanks to a comparison between the full-scaled and real-time results vs. the reduced-scale and accelerated-time results. Finally, the HIL reduced-scale and accelerated-time results obtained with a real battery are presented in Section IV.

II. MICROGRID SCALING

The scaling method considered in this paper is based on the similitude theory and a dimensional analysis, as done in several papers [10], [11]. According to these papers, the scaling of a system (here a microgrid) requires to modelize the system, then to carry out a dimensional analysis in order to finally determine the scaling factors and the scaled parameters. After a short description of the considered microgrid, the scaling method is explained in this section according to a dimensional analysis.

A. Microgrid description

The microgrid of an island is considered in this paper, as previously studied in simulation in [13]. An overview of the studied system is given in Fig. 1. It is composed of four renewable energy sources: solar photovoltaic panels, wind turbines, tidal turbines and wave energy converters. In order to ensure that the demand is met in case of a low generated power, lithium-ion batteries are used. The considered case study concerns the Ouessant Island (west coast of France). The energy management system of this microgrid, which includes Demand Side Management (DSM) strategies as described in [13] and the sources control, are out of the scope of this paper.

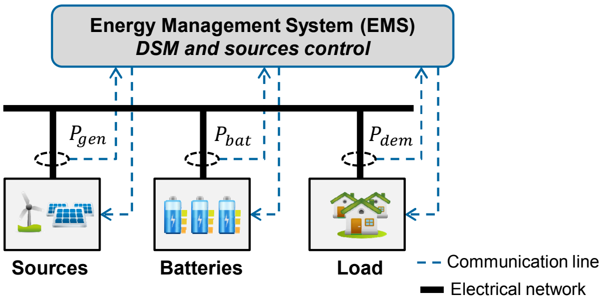

Fig. 1. Overview of the considered microgrid

The modeling approach considered in this paper is based on power flows. To simplify the study, the whole batteries are considered as a single battery. The battery management consists in charging the battery when the generated power is larger than the load power and discharging the battery if the load power is larger than the generated power. Thus, the battery power P_{bat} at each time sample t_k is defined as:

$$P_{bat}(t_k) = P_{gen}(t_k) - P_{dem}(t_k) \quad (1)$$

where P_{bat} is the battery power [W], P_{dem} the load power corresponding to the total demanded power of the island [W] and P_{gen} the total generated power by the four sources [W]. The battery power is considered to be positive in case of charge and negative in case of discharge.

The dynamic of this microgrid model is related to the battery state of charge (SoC). According to [14], the SoC is defined in case of charge ($P_{bat} > 0$) at each time sample t_k as:

$$SoC(t_k) = SoC(t_{k-1}) + P_{bat}(t_{k-1})\,\Delta t\,\eta_{bat}/C_{bat} \quad (2)$$

and in case of discharge ($P_{bat} < 0$) as:

$$SoC(t_k) = SoC(t_{k-1}) + P_{bat}(t_{k-1})\,\Delta t/(C_{bat}\,\eta_{bat}) \quad (3)$$

where C_{bat} is the battery capacity [Wh], P_{bat} the battery power [W], Δt the time step [h] and η_{bat} the battery efficiency.

The battery state of charge and the battery power are constrained by lower and upper limits:

$$SoC_{min} \leq SoC \leq SoC_{max} \quad (4)$$

$$P_{disch\ max} \leq P_{bat} \leq P_{ch\ max} \quad (5)$$

where SoC_{min} is the minimum allowed state of charge, SoC_{max} is the maximum state of charge, $P_{disch\ max}$ the maximum power in discharge [W] and $P_{ch\ max}$ the maximum power in charge [W].

B. Scaling method

The scaling process considered here is based on the methods applied in [8], [10], [11]. The similitude theory and the Vaschy-Buckingham theorem (also called Pi-theorem) state that two systems of the same nature have a similar behavior if their dimensionless variables have the same values [11], [15]. Thus, they present the same behavior whatever the scale considered. According to the Buckingham theorem, for a problem involving n physical parameters with r fundamentals units, it exists $p = n - r$ dimensionless variables necessary to represent the system [15]. These p variables are also called π-groups. Thus, the scaling method can be summarized as follows [11]:

- Identifying the n relevant physical parameters ;
- Setting the units in MKSA international system in order to identify the r fundamental units used ;
- Defining the parameters to be scaled ;
- Determining the p dimensionless π-groups ;
- Deducing the scaling factors and the scaled parameters.

These steps are developed in the following subsections.

1) Identification of the physical parameters

The relevant quantities influencing the dynamics of the microgrid operation are related to the variables used in (2) and (3). It exists n = 3 physical parameters with a dimension: C_{bat}, P_{bat} and Δt. The state of charge SoC and the efficiency η_{bat} are not taken into account as they are dimensionless, thus they remain the same in the full scale model and in the reduced scale model.

2) Dimensionnal analysis

The units of the related variables are set in the international MKSA system so as to simplify the dimensional analysis, as done in a lot of papers dealing with this subject [8], [10], [11], [16]. The MKSA units for each variable are given in Table I.

TABLE I. DIMENSIONAL ANALYSIS OF THE MICROGRID VARIABLES

Variable	SI Unit	MKSA Unit
C_{bat}	Ws	$m^2.kg.s^{-2}$
P_{bat}	W	$m^2.kg.s^{-3}$
Δt	s	s

As the fundamental units "m^2" and "kg" are always used together, they can be combined in a single unit "$m^2.kg$" in order to reduce the number of dimensions, as done in [8], [10]. Thus, the number of fundamental units used is $r = 2$ ($m^2.kg$ and s). According to the previous steps and the Vaschy-Buckingham theorem, the number of dimensionless variables necessary to represent the system is $p = n - r = 1$.

3) Definition of the parameters to be scaled

The next step of the method is to distinguish the parameters for which the scaling is freely chosen and the other parameters for which the scaling is deduced. The parameters of this first category are called in [8], [11] "repeating parameters" as they are used to scale the parameters of the second category. According to these references, the number of repeating parameters must correspond to the number r of fundamental units, in order to determine the p π-groups. As HIL tests with a reduced-size battery and an accelerated-time are carried out in this article, the battery capacity C_{bat} and the time step Δt are defined as the parameters for which the scaling will be chosen. Thus, the scaling factor related to the battery power P_{bat} will be deduced from the scaling factors related to C_{bat} and Δt. According to (1), the load power and the generated power will be scaled as the same way than the battery power. An overview of the full-scale model and the reduced scale model with the related parameters used in this study is given in Fig. 2. The parameters for the full scale case will be denoted with an F subscript and those used for the reduced scale case with an R subscript.

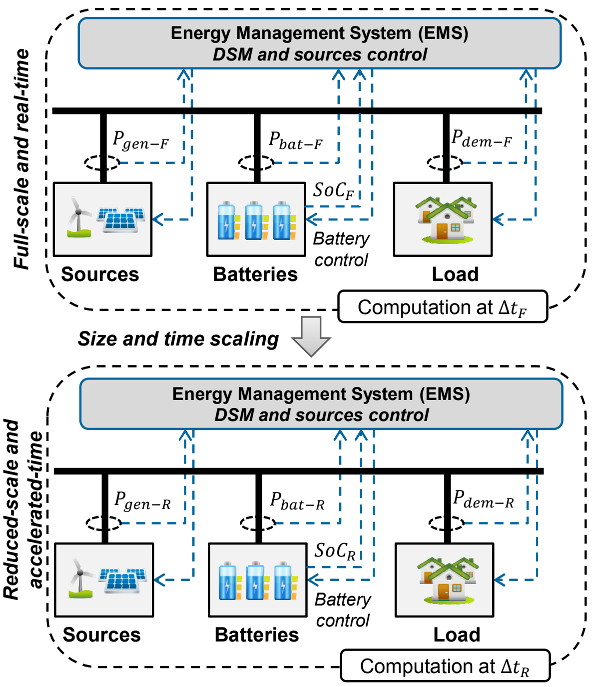

Fig. 2. Overview of microgrid parameters in both scales

4) Determination of the dimensionless π-groups

One dimensionless π-group exists for the considered study, which is related to the battery power and denoted Π_{Pbat}. It is defined as a combination of P_{bat} and the others parameters, such as:

$$\Pi_{Pbat} = P_{bat}\, C_{bat}^{\alpha}\, \Delta t^{\beta} \tag{6}$$

where α and β are the coefficients allowing Π_{Pbat} to be dimensionless. Thus, the solving of (6) in terms of dimensional similarity, by considering the units of Table I, leads to $\alpha = -1$ and $\beta = 1$:

$$\Pi_{Pbat} = P_{bat}\, C_{bat}^{-1}\, \Delta t^{1} \tag{7}$$

5) Scaling factors

The scaling factor is defined as the ratio between the scaled parameter and the initial parameter. Thus, the scaling factors S_{Cbat} for the battery capacity and $S_{\Delta t}$ for the time are defined as:

$$S_{Cbat} = C_{bat-R} / C_{bat-F} \tag{8}$$

$$S_{\Delta t} = \Delta t_R / \Delta t_F \tag{9}$$

where C_{bat-F} is the battery capacity at full scale [Wh], C_{bat-R} is the battery capacity at reduced scale [Wh], Δt_F is the time step at full scale (corresponding to the real time) [h] and Δt_R the time step at reduced scale (corresponding to the accelerated-time) [h].

The behavior of two systems (i.e. the full scale and the reduced scale systems) is similar if their dimensionless parameters have the same values. Thus, the dimensionless parameters Π_{Pbat-F} for the full scale and Π_{Pbat-R} for the reduced scale, which are defined as:

$$\Pi_{Pbat-F} = P_{bat-F}\, \Delta t_F \,/\, C_{bat-F} \tag{10}$$

$$\Pi_{Pbat-R} = P_{bat-R}\, \Delta t_R \,/\, C_{bat-R} \tag{11}$$

must be equal:

$$\Pi_{Pbat-F} = \Pi_{Pbat-R} \tag{12}$$

Thus, the rearrangement of (8), (9), (10), (11) and (12) leads to the scaling factor related to the battery power S_{Pbat}, defined as:

$$S_{Pbat} = P_{bat-R} / P_{bat-F} = S_{Cbat} \,/\, S_{\Delta t} \tag{13}$$

where P_{bat-F} is the battery power at full scale and P_{bat-R} the battery power at reduced scale [W].

Thus, the powers related to the reduced scale microgrid are defined as:

$$P_{bat-R} = P_{bat-F}\, S_{Cbat} \,/\, S_{\Delta t} \tag{14}$$

$$P_{gen-R} = P_{gen-F}\, S_{Cbat} \,/\, S_{\Delta t} \tag{15}$$

$$P_{dem-R} = P_{dem-F}\, S_{Cbat} \,/\, S_{\Delta t} \tag{16}$$

According to (13), the power scaling is influenced on the one hand by the choice of the battery capacity at reduced scale, and on the other hand by the choice of the time factor, depending on the desired acceleration. The power at reduced scale is decreased if the capacity of the battery at reduced scale is decreased, whereas it is increased if the time is accelerated. However, the power limits related to the HIL test bench must be taken into account. Thus, the battery power limits at reduced scale for the charge $P_{ch\ max\text{-}R}$ and the discharge $P_{disch\ max\text{-}R}$ must be scaled, without overpassing the limits $P_{ch\ max\ HIL}$ and $P_{disch\ max\ HIL}$ of the battery used for the HIL experiments:

$$P_{ch\ max\text{-}R} = \min\left(P_{ch\ max\text{-}F}\ S_{Cbat} / S_{\Delta t},\ P_{ch\ max\ HIL}\right) \quad (17)$$

$$P_{disch\ max\text{-}R} = \max\left(P_{disch\ max\text{-}F}\ S_{Cbat} / S_{\Delta t},\ P_{disch\ max\ HIL}\right) \quad (18)$$

III. Simulation Results

Before considering HIL experiments, the conservation of the dynamics when using the scaling method is checked by simulations. Thus, the behavior of the microgrid is evaluated in simulation for the case with full scale and real-time, then for the case with reduced scale and accelerated-time. The parameters related to both situations are given in Table II. The values of the battery parameters at the full scale are related to the Max+20M battery from Saft manufacturer, for which 30 batteries of 1.09 MWh per unit are considered. The reduced scale battery which will be used for HIL experiments was provided by the CEA. The installed power for each renewable source at the full scale is: 436.24 kW of photovoltaic panels, 8.1 MW of wind turbines, 1.5 MW of tidal turbines and 300 kW of wave energy converter. The considered technologies are described in [13]. The simulation is carried out on MATLAB SIMULINK over a 96 h period (for the real time case) according to resources data and load data related to Ouessant island, from 01/01/2011 to 04/01/2011 [17]. For the reduced scale case, the time step is divided by 6, thus six hours in real-time equals one hour in the test bench.

TABLE II. Parameters Values According to the Scale

Parameter	Full scale	Reduced scale
C_{bat}	$C_{bat\text{-}F}$ = 32.7 MWh	$C_{bat\text{-}R}$ = 18 kWh
$P_{ch\ max}$	$P_{ch\ max\text{-}F}$ = 66 MW	$P_{ch\ max\ HIL}$ = 90 kW
$P_{disch\ max}$	$P_{disch\ max\text{-}F}$ = -75 MW	$P_{disch\ max\ HIL}$ = -90 kW
SoC_{min}	$SoC_{min\text{-}F}$ = 0.1	$SoC_{min\text{-}R}$ = 0.1
SoC_{max}	$SoC_{max\text{-}F}$ = 0.9	$SoC_{max\text{-}R}$ = 0.9
η_{bat}	$\eta_{bat\text{-}F}$ = 0.96	$\eta_{bat\text{-}R}$ = 0.96
Δt	Δt_F = 6 s	Δt_R = 1 s
Simulated period	96 h	16h

According to the full scale and reduced scale parameters, the scaling factors can be calculated: S_{Cbat} = 18/32700, $S_{\Delta t}$ = 1/6, S_{Pbat} = 9/2725. Thus, according to (17) and (18), the battery power is limited by the reduced scale battery characteristics: $P_{ch\ max\text{-}R} = P_{ch\ max\ HIL}$ = 90 kW and $P_{disch\ max\text{-}R} = P_{disch\ max\ HIL}$ = -90 kW.

Fig. 3 shows the *SoC* obtained by a full scale/real-time simulation and by a reduced scale/accelerated-time simulation. The profiles related to the battery power, the generated power and the load power are given in Fig. 4, Fig. 5 and Fig. 6. These results show that the dynamic of the system is the same at both scales, as the state of charge decreases and increases in the same way along the considered period. Thus, the energy management system, which consists in controlling the loads and the sources according to the battery state of charge, operates similarly in both cases. For example, some of the sources are turned off at the beginning and at the end of the considered period. It can be noted that the battery power does not reach the charge and discharge power limits $P_{ch\ max\text{-}R}$ and $P_{ch\ max\text{-}R}$, which allows the dynamic of the system to be kept.

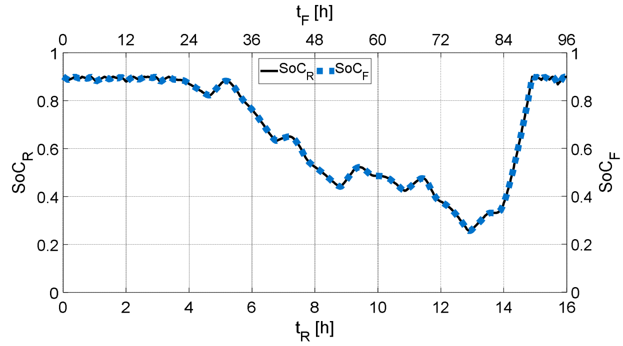

Fig. 3. *SoC* profiles obtained in simulation at both scales (full scale in red according to right and top axes, reduced scale in blue according to left and bottom axes)

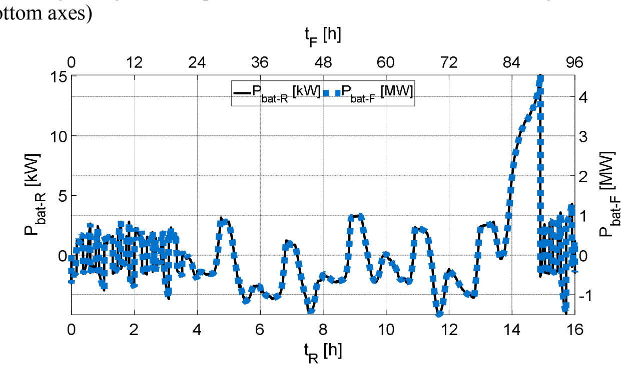

Fig. 4. P_{bat} profiles obtained in simulation at both scales

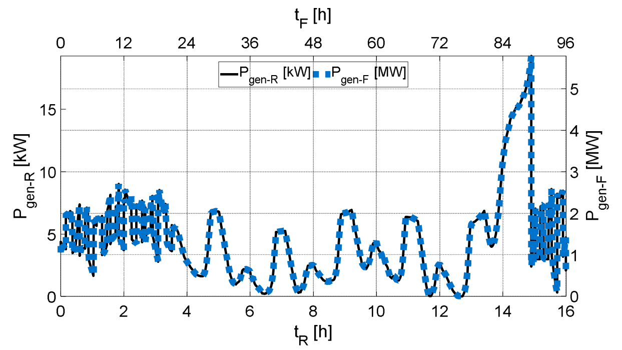

Fig. 5. P_{gen} profiles obtained in simulation at both scales

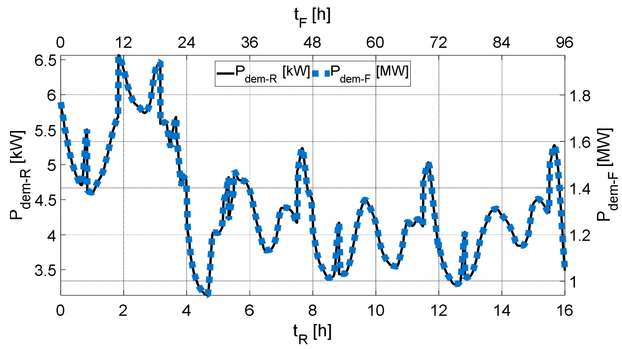

Fig. 6. P_{dem} profiles obtained in simulation at both scales

IV. EXPERIMENTAL RESULTS

The case considered in the previous section is applied here to a Power Hardware-In-the-Loop (PHIL) test bench in order to validate the EMS algorithm at a reduced scale and an accelerated-time.

A. Test bench description

The experimental test bench is presented in Fig. 7. The device under test is a lithium-ion battery for which the capacity is 18 kWh and the power limits are ± 90 kW. This battery is connected to the simulator via a DC power amplifier from Kratzer manufacturer. The microgrid model, developed under MATLAB SIMULINK software, is computed in accelerated-time by an Opal-RT target (OP5031). The fixed-step solver ode4 is use based on the Runge-Kutta method, with a time step of 1 s. The battery power setpoint is sent by the Opal-RT target to the DC power amplifier. The Battery Management System (BMS) returns the state of charge and the battery power measurements to the Opal-RT target so as to be used in the microgrid model. The OP5031 target is equipped with an Intel Xeon E5 3.2 GHz processor. The communication between the Opal-RT target and the BMS is done by UDP (User Datagram Protocol). A host computer is connected to the real-time target via a TCP/IP protocol in order to monitor the tests and display the signals.

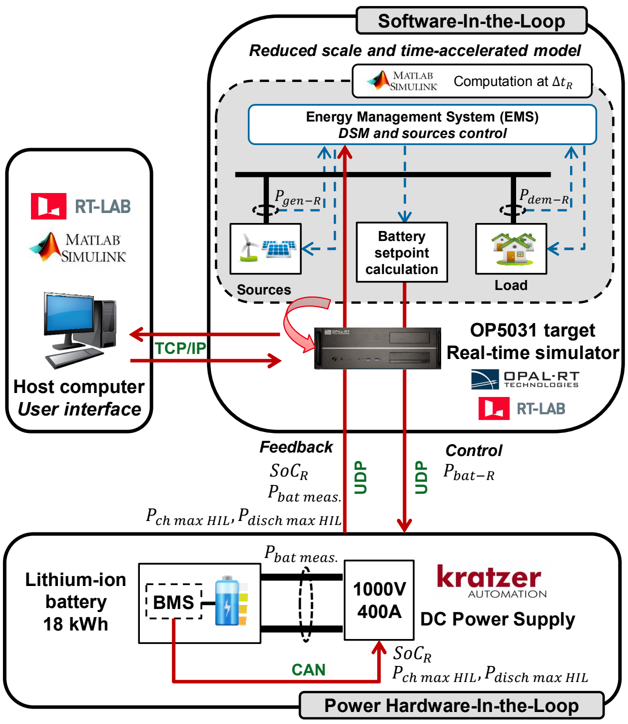

Fig. 7. Power Hardware-In-the-Loop test bench with a real battery

B. Results and discussion

The HIL experiment related to the reduced scale model with a real battery is computed during 16 h. The evolution of the *SoC* is given in Fig. 8. Fig. 9 shows the *SoC* error, defined as:

$$\Delta SoC_R(t_k) = SoC_{R\text{-}HIL}(t_k) - SoC_{R\text{-}simu}(t_k) \qquad (19)$$

According to the error and the battery power given in Fig. 10, the obtained results show a slight difference between the HIL test and the simulation, but the *SoC* error does not overpass -0.02 and +0.022. The main reason comes from that the *SoC* sent by the BMS is quantized with a 0.5 % step, which influences the microgrid behavior. Indeed, the control of the sources and the loads done by the EMS algorithm is related to the *SoC* value. Thus, the EMS algorithm does not receive at the same time in the simulation and in the HIL test the information that the battery is at its maximum state of charge, which modifies the time at which the sources are turned off. So as to confirm the influence of the quantization of the *SoC*, the simulation is carried out by rounding the *SoC* value to within 0.5 %. The *SoC* error between this simulation and the HIL test is given in Fig. 11. The results show that the error is reduced, as its value does not overpass -0.02 and +0.015. Thus, the difference can be partially explained by the quantization of the *SoC*, but others factors such as the temperature can influence the efficiency of the battery, so the *SoC*.

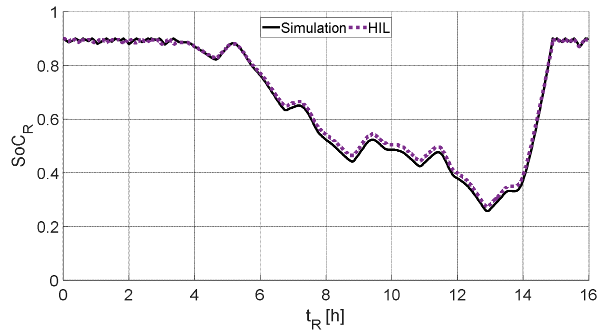

Fig. 8. Comparison of *SoC* profiles at reduced scale between HIL experiment vs. simulation

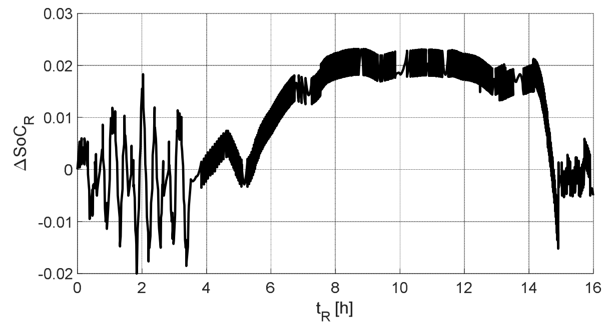

Fig. 9. *SoC* error between HIL experiment and simulation

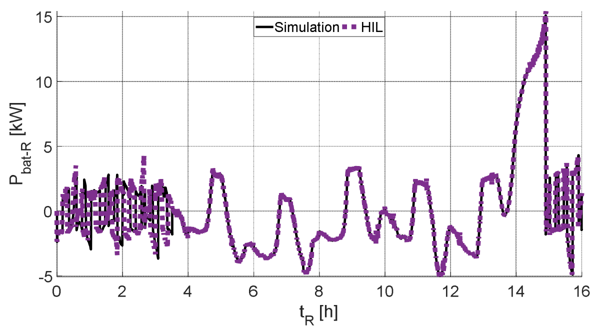

Fig. 10. Comparison of P_{bat} profiles at reduced scale between HIL experiment vs. simulation

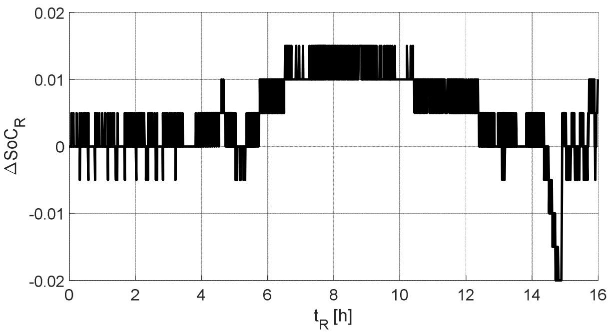

Fig. 11. *SoC* error between HIL experiment and simulation with rounded *SoC*

A comparison of the energy exchanged by the battery in charge and in discharge over the whole period for the three different cases is proposed in TABLE III. The energy is normalized by the battery capacity, in order to make the comparisons possible. The results show that in simulation the ratios have the same values for both models, in charge and discharge, whereas a small difference is observed in the HIL test. These observations confirm that the scaling method allows the behavior of the system to be conserved. The difference between the HIL tests and the simulation with the reduced scale model can be related to the quantization of the *SoC* values provided by the BMS, as seen in Fig. 11. Moreover, the difference could be related to the efficiency of the battery used for the HIL test. Indeed, the efficiency depends on the chemical and the thermal characteristics of the battery and the operating conditions, which are not taken into account in the simulation model as a constant value is considered ($\eta_{bat-R} = 0.96$).

TABLE III. COMPARISON OF THE ENERGY EXCHANGED BY THE BATTERY

Case	Simulation: full-scale and real-time	Simulation: reduced-scale and accelerated-time	HIL: reduced-scale and accelerated-time
Energy in charge	E_{ch-F}/C_{bat-F} =1.099	E_{ch-R}/C_{bat-R} = 1.099	E_{ch-R}/C_{bat-R} = 1.103
Energy in discharge	$E_{disch-F}/C_{bat-F}$ = 1.096	$E_{disch-R}/C_{bat-R}$ = 1.096	$E_{disch-R}/C_{bat-R}$ = 1.092

V. CONCLUSION

The scaling method used in this paper allows the behavior and the dynamics of the microgrid model to be kept in HIL experiments. Accelerating time allows the duration of the experiments to be reduced, which allows long periods of data to be assessed in case of HIL tests, thus different kinds of situations such as variations of resources and load. However, some constraints related to the reduced scale, due to the power limits of the device under test for example, can bring nonlinearities compared to the full scale model. Moreover, as the time reduction increases the powers, the choice of the time scaling factor must take the power limits of the experimental test bench into account in order to keep the dynamics.

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