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## SCALING OF WIND ENERGY CONVERSION SYSTEM

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**Abstract** – This paper presents a scaling methodology based on dimensional analysis and applicable to systems' mathematical models. The main goal of this research is to propose time-compressed HIL experiments together with reduced power, while keeping similarity with respect to the dynamics of the original system. The scaling process is presented using a simple wind turbine model. This reduced model is validated through a simulation in which the wind conversion system is connected to a scaled electrochemical battery.

**Keywords** – Wind System, Similarity, Scaled Systems, Time Acceleration, HIL, Buckingham Pi Theorem, Dimensional Analysis.

### 1. INTRODUCTION

The global energy landscape is constantly evolving. Emergence of new environmental objectives, the development of renewable energies and new uses of electricity (heat pump, electric car, etc.) require modernization of electricity networks. This latter issue is coupled with the optimization of the management of electrical production which promises energy savings. In this framework, stages of modeling, simulation and experimentation become key issues.

Nevertheless, the experimental phase can be difficult when systems are complex. The related cost is huge especially for high power systems as for wind production. Therefore it is advisable to use scaled models to decrease the experiment cost. As numerical simulations make possible to deduce the characteristics of the phenomena in real size, reduced scale physical emulation based on Hardware in the Loop (HIL) experiments minimize the risks associated with the experiments and decrease associated costs; such process aims at experimentally validate the simulations especially dynamic (real time) aspects related to control and management of power systems. Moreover, these similarity models also allow to envisage simulated experimentation (concept of physical emulation) in "compacted virtual time" which makes more efficient (being more rapid) the validation process. The notions of similarity will have to achieve relevant scale reductions and so they are as useful in sizing models for system engineering as for models built into physical emulators.

The laws of physics are invariant with respect to any change of unity. This invariance notion is essential. It allows to define the behavior of a physical system

by a complete set of dimensionless variables formed by relevant physical variables. Then it is possible to compare the systems with each other by comparing their dimensionless quantities. The Vaschy-Buckingham theorem [1] (or  $\Pi$  theorem), basic theorem of dimensional analysis, allows to set how many independent dimensionless numbers can be constructed in a physical problem that involve  $n$  variables.

In the remainder of this report, we will first present the similitude theory and the general method of system scaling before to present some simulations.

### 2. SIMILITUDE THEORY

The purpose of dimensional modeling is to carry out experiments on a scaled-model system, and then to be able to project the obtained results on the full-scaled system.

Similitude theory is a branch of engineering science concerned with establishing the necessary and sufficient conditions of similarity among phenomena. According to this theory, two systems have the same behavior (under the same experimental conditions) if their dimensionless variables have the same values, respectively [2]. This property allows to study the behavior of a system by carrying out experiments on another system (here an emulated system), similar to the first, but with a more practical (reduced and cost effective) physical scale.

Therefore, the similitude theory has the following objectives :

- Proposing independent dimensionless numbers (called  $\pi$ -groups);

- Simplifying basic equations by removing irrelevant variables;
- Establishing criteria to be fitted for a scale experiment in order to be representative of a full-scale phenomenon;
- Providing the scale change relationships between “scale one” and reduced scale experiments.

The use of the Buckingham theorem allows to go from the study of a physical problem having  $n$  variables to a problem of dimension  $k = n - r$  expressed in terms of dimensionless numbers (with  $r$  the number of independent physical dimensions).

## 2.1. DIMENSIONAL ANALYSIS

In engineering and science, dimensional analysis is related to the relationships between different physical quantities by identifying their fundamental dimensions. It is a powerful tool widely used for scale model calculation [3],[4].

Nondimensionalization procedure is started by identifying the number  $n$  of relevant physical quantities (variables and parameters) used to describe the behavior of the system. Secondly, setting their units in the international MKSA system is also necessary, which allows to calculate the number  $r$  of independent fundamental dimensions.  $r$  also represents the number of available degrees of freedom (i.e. the number of independent variables that can be scaled).

Examples:

- transforming the newton [N] unit in the MKSA system: according to the weight formula  $P[N] = m[kg] \times g[m/s^2]$ , the newton is expressed in fundamental units as follows:  $1 N = 1 kg.m.s^{-2}$ .
- transforming the joule [J] unit in the MKSA system: according to the formula of kinetic energy  $E[J] = \frac{1}{2}m[kg].v^2[m^2/s^2]$ :  
 $1 J = 1 kg.m^2.s^{-2}$

The number  $k$  of  $\pi$ -groups necessary to represent the system studied is calculated as follows [1]:

$$k = n - r \quad (1)$$

From this information, a table composed of 4 matrices A, B, C, D is constructed.

### I. Construction of the dimensional set matrix

	Parameters/ variables	Repeating Parameters
Fundamental Units	B	A
$\pi$ -groups	D	C

- The entries of matrices A and B are the exponents associated with the fundamental dimensions of the unit of the parameter/variable.
- Repeating parameters can be chosen arbitrarily provided that the matrix A is invertible. However, it is wise to choose the parameters that will be scaled to simplify the calculations.
- The matrix D must be of the simplest form possible in order to have the simplest possible  $\pi$ -groups. It is usual to use the identity matrix which makes it possible to have a decoupling between  $\pi$ -groups and the parameters/variables of the model to be reduced : each  $\pi$ -group depends on a single parameter/variable as well as on certain repeating parameters.
- Matrix C is calculated as follows:

$$C = -D(A^{-1}B)^T \quad (2)$$

Details can be found in [4]

Then this table allows to determine expressions of the different  $\pi$ -groups which are a combination of a single parameter/variable and repeating parameters.

Some examples of this matricial derivation are provided in section 3.

## 2.2. SCALE FACTOR

In order to determine the scaled model parameters, we introduce the notion of "scale factor". A scale factor  $S_x$  always refers to a particular physical variable  $x$  and is defined as the quotient of the scaled variable and the original variable:

$$S_x = \frac{x_{scaled}}{x_{original}} \quad (3)$$

Each variable or parameter corresponds to a scale factor which can be expressed directly from the  $\pi$ -group associated to it through a relation that forms a particular model called «Model Law».

As mentioned before, two systems of the same kind have the same behavior (under the same experimental conditions) if their dimensionless variables have the same values, respectively. Consequently the scale factors of  $\pi$ -groups must be equal to 1 in order for the reduced model to have the same dynamics as the original model. Thus, the scale factor of a variable can be determined from the expression of the  $\pi$ -groups associated with it (this expression will be a function of the repeating parameters).

A general method for scaling a system emerges:

- 1) Determination of relevant physical variables ;

- 2) Dimensional analysis (MKSA units) ;
- 3) Choice of variables to be scaled (repeating parameters) ;
- 4) Calculation of  $\pi$ -groups ;
- 5) Determination of scale factors ;
- 6) Calculation of scaled model parameters.

### 3. APPLICATION TO A WIND ENERGY CONVERSION SYSTEM

In order to present the similitude theory, a simplified case study that has relatively few physical variables has been selected; for example, actual generator – power electronic association has been replaced by an “energetically equivalent” DC machine supplying a DC-DC chopper. The source device consists of a wind turbine, a rotating shaft with inertia and an electric machine that ensures electromechanical conversion.

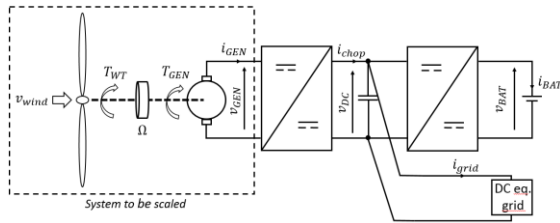


Fig. 1. Wind energy conversion system

#### 3.1. SYSTEM MODELING

The torque  $T_{WT}$  produced by the blades depends on the wind velocity:

$$T_{WT} = \frac{1}{2} C_T(\lambda) \rho S R v_{wind}^2 \quad (4)$$

$$C_T(\lambda) = \frac{C_P(\lambda)}{\lambda}$$

$C_P(\lambda)$  (power coefficient) is obtained by polynomial interpolation from datasheet of the turbine. It is a non-linear function of the tip speed ratio  $\lambda$ , a dimensionless quantity depending on the wind speed  $v_{wind}$ , the shaft speed  $\Omega$  and the blade radius  $R$ :

$$\lambda = \frac{R\Omega}{v_{wind}} \quad (5)$$

In addition, the swept area of the wind turbine is a function of the blade radius :

$$S = \pi R^2 \quad (6)$$

In our case study, we take into account the torque drop caused by the turbine inertia  $J$ , but friction effects are neglected:

$$J \frac{d}{dt} \Omega = T_{WT} - T_{GEN} \quad (7)$$

In the studied system, the electromechanical conversion is provided by a permanent magnet DC machine instead of the AC machine classically used in wind generation system. Let us note that the DC machine is seen as energetically equivalent to a vector controlled inverter fed PM synchronous machine or induction machine but with a simpler model. Classical modeling is used:

$$\begin{cases} e_{GEN} = k_\phi \Omega \\ T_{GEN} = k_\phi i_{GEN} \end{cases} \quad (8)$$

$$v_{GEN} - e_{GEN} = - \left( r i_{GEN} + L \frac{di_{GEN}}{dt} \right)$$

#### 3.2. SYSTEM SCALING

##### II. Dimensional analysis of the wind energy conversion system

Variable	Symbol	MKSA unit
Wind speed	$v_{wind}$	$m \cdot s^{-1}$
Wind turbine torque	$T_{WT}$	$m^2 \cdot kg \cdot s^{-2}$
Generator torque	$T_{GEN}$	$m^2 \cdot kg \cdot s^{-2}$
Shaft rotation speed	$\Omega$	$s^{-1}$
DC machine current	$i_{GEN}$	A
DC machine e.m.f.	$e_{GEN}$	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
DC machine voltage	$v_{GEN}$	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
Time	$t$	s
Air density	$\rho$	$m^{-3} \cdot kg$
Blade radius	$R$	m
Wind turbine inertia	$J$	$m^2 \cdot kg$
Flux coefficient	$k_\phi$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
DC machine inductance	$L$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
DC machine resistance	$r$	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$

The dimensional analysis of the system is carried out by selecting relevant quantities (for example, the active surface of the wind turbine is not selected being directly calculated from the rotor radius).

Thus we find  $n = 14$  relevant physical quantities (see table II), and  $r = 4$  independent fundamental dimensions ([m], [kg], [s], [A]). Therefore, according to the Vaschy-Buckingham theorem (1), we need 10  $\pi$ -groups to describe the electro-mechanical conversion chain ( $14 - 4 = 10$ ). There are 4 degrees of freedom (repeating parameters), and we choose to scale the quantities  $\rho$ ,  $i_{GEN}$ ,  $v_{GEN}$  and  $t$  in order to create the dimensional set matrix associated with this system (see Table III).

### III. Dimensional set matrix

	$v_{wind}$	$T_{WT}$	$T_{GEN}$	$\Omega$	$e_{GEN}$	$R$	$J$	$k_\phi$	$L$	$r$	$\rho$	$t$	$u_{GEN}$	$i_{GEN}$
[m]	1	2	2	0	2	1	2	2	2	2	-3	0	2	0
[kg]	0	1	1	0	1	0	1	1	1	1	0	0	1	0
[s]	-1	-2	-2	-1	-3	0	0	-2	-3	0	0	1	-3	0
[A]	0	0	0	0	-1	0	0	-1	-2	-2	0	0	-1	1
$\pi_{v_{wind}}$	1	0	0	0	0	0	0	0	0	0	0,2	0,4	-0,2	-0,2
$\pi_{T_{WT}}$	0	1	0	0	0	0	0	0	0	0	0	-1	-1	-1
$\pi_{T_{GEN}}$	0	0	1	0	0	0	0	0	0	0	0	-1	-1	-1
$\pi_\Omega$	0	0	0	1	0	0	0	0	0	0	0	1	0	0
$\pi_{e_{GEN}}$	0	0	0	0	1	0	0	0	0	0	0	0	-1	0
$\pi_R$	0	0	0	0	0	1	0	0	0	0	0,2	-0,6	-0,2	-0,2
$\pi_J$	0	0	0	0	0	0	1	0	0	0	0	-3	-1	-1
$\pi_{k_\phi}$	0	0	0	0	0	0	0	1	0	0	0	-1	-1	0
$\pi_L$	0	0	0	0	0	0	0	1	0	0	0	-1	-1	1
$\pi_r$	0	0	0	0	0	0	0	0	1	0	0	0	-1	1

Example: Torque  $T_{WT}$  is expressed in  $m^2 \cdot kg \cdot s^{-2}$ . Its column is filled with the vector [2;1;-2] representing exponents associated with the fundamental dimensions.

From this table, we deduce the following  $\pi$ -groups:

$$\begin{aligned}
 \pi_{v_{wind}} &= \frac{v_{wind} \rho^{0,2} t^{0,4}}{u_{GEN}^{0,2} i_{GEN}^{0,2}} & \pi_{T_{WT}} &= \frac{T_{WT}}{t u_{GEN} i_{GEN}} \\
 \pi_{T_{GEN}} &= \frac{T_{GEN}}{t u_{GEN} i_{GEN}} & \pi_\Omega &= \Omega t \\
 \pi_{e_{GEN}} &= \frac{e_{GEN}}{u_{GEN}} & \pi_R &= \frac{R \rho^{0,2}}{t^{0,6} u_{GEN}^{0,2} i_{GEN}^{0,2}} \\
 \pi_J &= \frac{J}{t^3 u_{GEN} i_{GEN}} & \pi_{k_\phi} &= \frac{k_\phi}{t u_{GEN}} \\
 \pi_L &= \frac{L i_{GEN}}{t u_{GEN}} & \pi_r &= \frac{r i_{GEN}}{u_{GEN}}
 \end{aligned} \quad (9)$$

Then we obtain the scale factors of the variables according to the repeating parameters:

$$\begin{aligned}
 S_{v_{wind}} &= \frac{S_{u_{GEN}}^{0,2} S_{i_{GEN}}^{0,2}}{S_\rho^{0,2} S_t^{0,4}} & S_{T_{WT}} &= S_t S_{u_{GEN}} S_{i_{GEN}} \\
 S_{T_{GEN}} &= S_t S_{u_{GEN}} S_{i_{GEN}} & S_\Omega &= \frac{1}{S_t} \\
 S_{e_{GEN}} &= S_{u_{GEN}} & S_R &= \frac{S_t^{0,6} S_{u_{GEN}}^{0,2} S_{i_{GEN}}^{0,2}}{S_\rho^{0,2}} \\
 S_J &= S_t^3 S_{u_{GEN}} S_{i_{GEN}} & S_{k_\phi} &= S_t S_{u_{GEN}} \\
 S_L &= \frac{S_t S_{u_{GEN}}}{S_{i_{GEN}}} & S_r &= \frac{S_{u_{GEN}}}{S_{i_{GEN}}}
 \end{aligned} \quad (10)$$

Therefore, scaled model parameters are calculated from the original model parameter:

$$\begin{aligned}
 (v_{wind})_{scaled} &= \frac{S_{u_{GEN}}^{0,2} S_{i_{GEN}}^{0,2}}{S_\rho^{0,2} S_t^{0,4}} (v_{wind})_{ori} \\
 (T_{WT})_{scaled} &= S_t S_{u_{GEN}} S_{i_{GEN}} (T_{WT})_{ori} \\
 (T_{GEN})_{scaled} &= (T_{WT})_{ori}
 \end{aligned} \quad (11)$$

$$(\Omega)_{scaled} = \frac{1}{S_t} (\Omega)_{ori}$$

$$(e_{GEN})_{scaled} = S_{u_{GEN}} (e_{GEN})_{ori}$$

$$(R)_{scaled} = \frac{S_t^{0,6} S_{u_{GEN}}^{0,2} S_{i_{GEN}}^{0,2}}{S_\rho^{0,2}} (R)_{ori}$$

$$(J)_{scaled} = S_t^3 S_{u_{GEN}} S_{i_{GEN}} (J)_{ori}$$

$$(k_\phi)_{scaled} = S_t S_{u_{GEN}} (k_\phi)_{ori}$$

$$(L)_{scaled} = \frac{S_t S_{u_{GEN}}}{S_{i_{GEN}}} (L)_{ori}$$

$$(r)_{scaled} = \frac{S_{u_{GEN}}}{S_{i_{GEN}}} (r)_{ori}$$

As can be seen, in order to keep the same dynamics for the scaled model as for the original model, it is necessary to define a “virtual wind” calculated according to the scaled variables. It is possible to keep the value of the real wind, but at the expense of a degree of freedom.

### 4. SIMULATION RESULTS

The simulated system is composed of the previous wind energy conversion system, a battery and a load that represents the network (Fig. 1).

The power converters are modeled by replacing the switching and modulation functions by their mean values calculated on the switching period. Since the duty cycle is a dimensionless variable, it will not be scaled.

The battery model is based on the Tremblay-Dessaint model [5], which scaling is carried out in [6]. This is a commonly used model which allows accurately representing the dynamic behavior of electrochemical batteries with an easy parametrization method. readers will find every modelling details in refs [5,6].

$$\begin{aligned}
 \frac{d}{dt} SoC &= -\frac{1}{Q} i \\
 \frac{d}{dt} i^* &= -\frac{1}{T_f} i^* + \frac{1}{T_f} i \\
 v_{bat} &= E_0 - Ri - K_1 Q \left( \frac{1}{SoC} - 1 \right) \\
 &\quad - K_2 i^* \left( \frac{n_{dch}}{SoC} \right) \\
 &\quad + \frac{n_{ch}}{1,1 - SoC} \\
 &\quad + A e^{-BQ(1-SoC)}
 \end{aligned} \quad (12)$$

## 4.1. SYSTEM ELEMENTS CHARACTERISTICS

DC machine parameters are calculated from an equivalence with a synchronous machine admitting a nominal power of 2 MW [7]. The characteristics of the wind chain can be found in Tables IV and V:

IV. Wind turbine characteristics [7]

Parameters	Values
Rated WT speed	12,5 m/s
Rated power	2000 kW
Rotational speed	8-24 tr/mn
Rotor diameter	75 m
WT inertia	$6,2 \cdot 10^6$ kg.m <sup>2</sup>

V. Synchronous generator parameters [7]

Parameters	Values
Rated shaft power	2,16 MW
Rated torque	790 kNm
Rated frequency	13 Hz
Rated voltage	1,75 kV
Rated current	660 A
Number of pole-pairs	32

The battery model parameters are obtained from the data presented in [8], giving the cell parameters from SAFT VL41M batteries. Then, the number of cells in series and in parallel is calculated in order to obtain the current and voltage levels comparable to those of the wind turbine.

VI. Parameters for a Li Ion SAFT VL41M cell [8]

Parameters	Values
Battery constant voltage $E_0$	3,24 V
Exponential amplitude $A$	0,75 V
Exponential zone time constant inverse $B$	$0,03 \text{ Ah}^{-1}$
Battery capacity $Q$	41 Ah
Polarization constant $K_1$	$1,04 \times 10^{-4} \text{ V/Ah}$
Polarization resistance $K_2$	$1,04 \times 10^{-4} \Omega$
Internal resistance $R$	1,97 m $\Omega$
Current-filter time constant $T_f$	30 s

## 4.2. SIMULATION RESULTS

In this simulation, a simplified textbook case is used: the battery is initially charged at 80% and the wind turbine, facing a constant rated wind speed, provides power. At  $t = 200$ s, the grid requires a power such that  $P_{\text{grid}} < P_{\text{GEN}}$  in order to continue the battery charge until a SOC of 90%. Finally, production of the wind turbine is degraded up to  $P_{\text{GEN}} = P_{\text{grid}}$  (see Fig. 2).

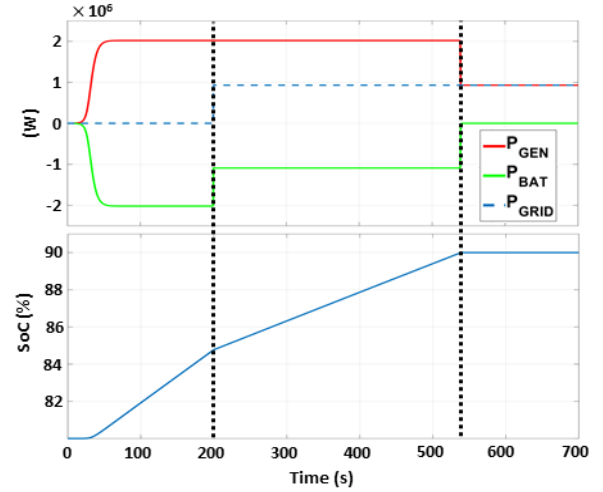


Fig. 2. Simulation scenario

The air density is supposed to be unchanged during scaling ( $S_\rho = 1$ ). Based on table III, it remains 3 degrees of freedom for scaling with  $t$ ,  $i_{\text{GEN}}$  and  $v_{\text{GEN}}$ .

Two simulations are carried out: a first performed at real time without scaling, and a second with current, voltage and time-scaling by a factor of 1/10.

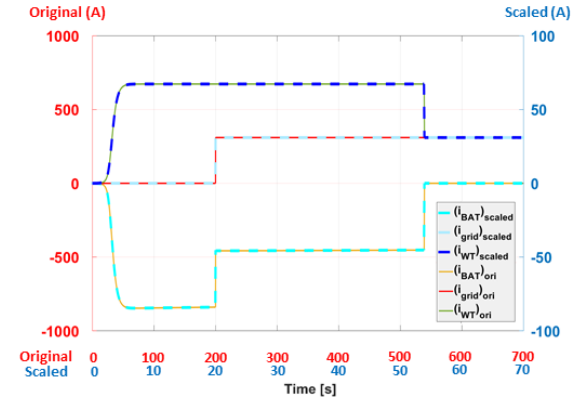


Fig. 3. Original vs scaled currents

Observing all currents of both studied systems allows not only to validate the current and time-scalings, but also the different steps of the energy management during our textbook case. The dynamics between both models are respected, showing that the two models are in similitude. In the same way, Fig. 4 allows to validate voltage-scaling for the battery.

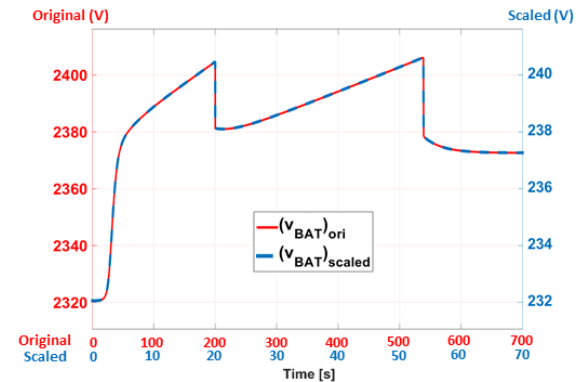


Fig. 4. Comparison between original battery voltage and scaled battery voltage

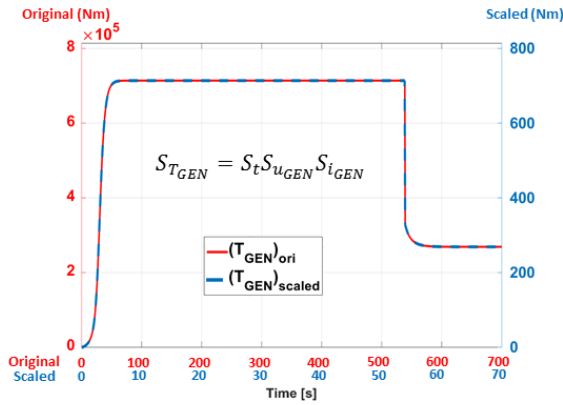


Fig. 5. Comparison between original generator torque and scaled generator torque

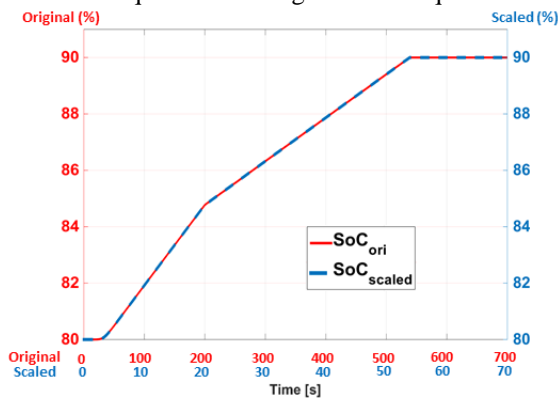


Fig. 6. Comparison between original SoC and scaled SoC

As can be seen in Fig. 5, the torque scale factor is a combination of the three scales which means that we have a torque 1000 times lower in the case of the model. Finally, the observation of the state of charge (Fig.6) is very interesting since this variable does not take part in the calculation of the scaled model parameters but is an important indicator. Then we see that there is no difference between our two simulations. Therefore, we can conclude that we performed the same test twice, but the second at power levels 100 times smaller and 10 times faster.

## 5. CONCLUSIONS

The work presented in this report represents a first step towards the design of emulators. They allowed the development of a methodology to adopt to calculate the parameters of a reduced model :

- Determination of relevant physical variables ;
- Dimensional analysis of the system;
- Choice of the repeating parameters (parameters to be freely scaled) ;
- Determination of  $\pi$ -groups ;
- Determination of scale factors ;
- Calculation of scaled model parameters.

Moreover, we have shown that the connection between several scaled models is possible, which is an important step in the design of a micro-network. One of the next steps in this work will be to study the modularity of this method in order to determine the connection rules between several scaled models. Similarly, the last simulations show that in a simple case the scaling of a model allowed the conservation of an energy management strategy.

In addition, experimentations are expected in order to validate these results. These tests will lead us to question on the limits of scaling, especially in the case of time.

Finally, using more complex models will be necessary in order to take into account a maximum of phenomena present in the physical systems and to tend towards a smart micro-network representative of reality.

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