Experimental set-up to test the power transfer of an innovative subway using supercapacitors

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***Abstract*- A new subway traction system has been proposed without supply rail. The on-board energy is stored in a supercapacitor bank. This energy storage system is charged at each station in order to have enough energy to reach the next station. In-station supercapacitors are also used to ensure a fast charge of the on-board supercapacitors. Before implementation of this new supply system, a reduce-scale experimental set-up is developed in order to test the different energy flows in real time. First experimental results are provided.**

Keywords- energy storage system, hardware-in-the-loop simulation, traction drive, supercapacitors

I. INTRODUCTION

Energy saving is a critical issue for the next decade. The development of new transportation systems takes a part in this challenge [1]-[4]. Trains, tramways and subways have been developed a long time ago, and they provide efficient systems for passenger transportation in urban cities. Classical subways are supplied by a specific DC rail. Their efficiency is generally very high because their traction is ensured by electric drives. Moreover, regenerative braking can be used to re-inject electrical current through the DC rail. The energy recovery is possible only if other vehicles on the line are able to absorb this energy. When it is not the case, all braking energy is dissipated in a braking resistor and/or a mechanical brake. New storage systems are developed to increase the energy recovery, such as new batteries [5], flywheels [6][7], supercapacitors [8][9] or hybrid energy storage systems [10].

A new subway without supply rail is actually developed to propose a more efficient subway traction system and a reduction of the infrastructure. This subway uses an on-board supercapacitors bank as Energy Storage System and no supply rail is used between stations. [11][12]. The on-board supercacitor is charged at each station. When the subway accelerates the on-board supercacitor is discharged. When the subway decelerates, the regenerative braking charges the on-board supercacitor. In this way, the energy saving can be increased. Moreover the operation without supply rail between stations reduces significantly the infrastructure. A simulation model has been developed to analyze the power flows and control schemed of this new traction system [13]. Hardware-in-the-loop (HIL) simulation has also been used to check the ability of the control to manage energy flows of the on-board supercapacitor in real time during traction operations [12].

In this paper, a new experimental set-up is presented in order to test and validate the charge of the ESS at the station using an in-station supercapacitor bank and an on-board supercapacitor bank.

II. NEW SUBWAY TRACTION SYSTEM USING SUPERCAPACITORS

A. *Principle of the new subway traction system*

The studied subway is a new system without supply rail. An on-board supercapacitor bank (SC2) supplies the subway between two stations (Fig. 1). This on-board ESS2 is sized to provide enough energy to reach the next station in the worst case (maximum slope, front wind, etc). The on-board SC2 must be recharged quickly at each station. An in-station supercapacitor bank (SC1) is used to ensure a fast charge of the on-board SC2.

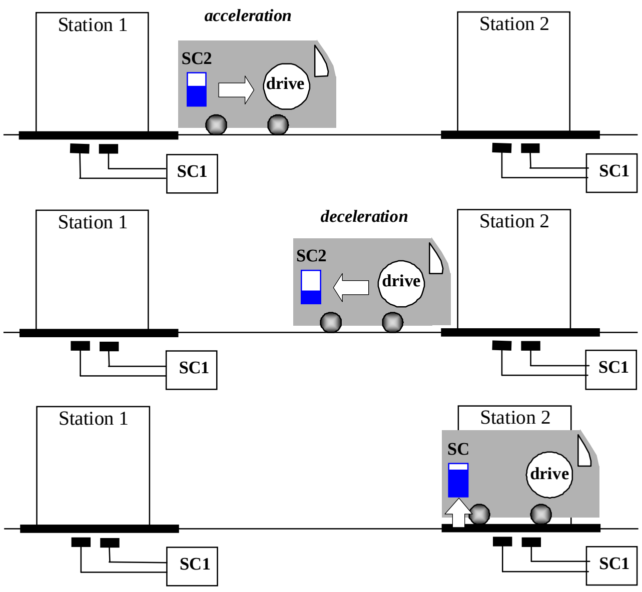

Fig. 1. Principle of the new subway traction system

B. *Supply system in station*

The in-station SC1 is recharged via the electrical grid by a PWM rectifier and a chopper (Fig. 2). During the power

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transfer between the in-station SC1 and the on-board SC2, two choppers are used through a DC bus. In this first study, the connection system between the subway and the station is not taken into account. It will be studied in later steps. Different transfer strategies have been studied in simulation [13]. But an experimental validation is required before an implementation in the real subway traction system.

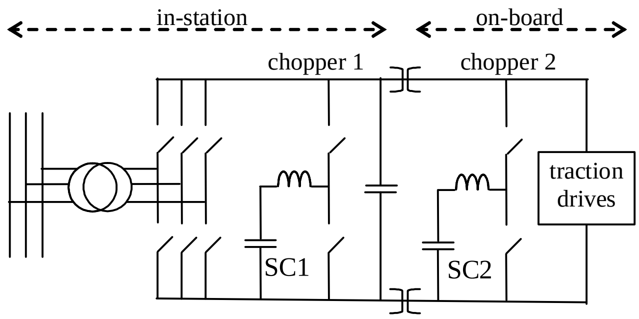

Fig. 2. Supply system in station for the new subway

C. On-board energy management

During the cycle between both stations, the supply system is disconnected. The on-board SC2 ensure alone the traction power and the recovery of energy during the deceleration phase. Different strategies have also been developed for the on-board energy management [13]. This new control algorithm has now be tested in real time

D. Inversion-based control

The whole system has been simulated using Energetic Macroscopic Representation (EMR, see appendix), which is a graphical description for power flow analysis and control design [14]. An inversion-based control has been deduced from the EMR of the system (Fig. 3), and simulation results have been provided for different cases [13]. This new control algorithm has been tested in real time using a single supercapacitor bank and HIL simulation [12].

III. Hardware-In-the-Loop Simulation

Before an implementation on a real vehicle, different tests have to be provided. Hardware-In-the-Loop (HIL) simulation is used to organize the different steps [15]. First a reduced-scale HIL simulation validates the principle of the new subway supply in real-time using reduced-power components. In a second step, a full-power HIL simulation can be developed to test the full-power energy storage system in a static way. Finally, this full-power energy storage system will be implemented in a prototype vehicle using a specific test track. Only the first step is studied in this paper.

A. Principle of HIL simulation

In HIL simulation, on part the real system is inserted in the simulation loop. This method yields preliminary tests of this physical device before its implementation in the whole system. Signal HIL simulation has been used for a long time to test ECU (Electronic Control Unit) in aerospace and automotive applications [16]. More recently, power HIL simulation has been developed to test power devices such as inverters, electrical machines or propulsion subsystems [17][15].

In some cases, a full power device can not be used for preliminary test for safety and cost reasons. Reduced-scale HIL simulation is thus used using a reduced-power device. Specific adaptation ratios are defined in order to keep the HIL simulation close to the real system despite the reduced-power devices [15].

B. HIL simulation of the new energy storage system

First simulations have been developed to test the possibilities of this new subway system and to tune the different controllers. A specific control has thus been defined.

The principle of the supply system using the two supercapacitor banks and the energy management must now be validated in real time. But, due to the high cost of supercapacitors and also the high power during the different operations, a reduced HIL simulation has been chosen for these preliminary tests.

In this case, the sub-system to test is composed of the supply system in station (including the in-station SC1) and the on-board SC2. This subsystem under test must be connected to another power device (emulation device), which has to reproduce the same behavior of the vehicle traction subsystem (Fig. 4). In some cases, a reduced-scale traction drive with a load drive can be used [11][15]. In this study, a simple chopper is used (Fig. 5) in order to focus on the two ESSs. This emulation chopper is controlled to reproduce the traction current using a mathematical model of the subway traction subsystem. When the subway is at a standstill, no current is provided. When the subway accelerates, a positive current is generated in function of the required torque. When the subway decelerates, a negative current is imposed proportionally to the recovery power.

The full-scale subway mathematical model (traction drive, mechanical powertrain, subway environment and control) is used. First, this model is derived from the real vehicle and it is composed of non linear parts, which are difficult to reproduce in a reduced-scale model. Secondly, this full-scale model will be used when the full-scale HIL simulation is developed. In order to connect the full-scale model to the reduced-scale power devices, adaptation coefficients are defined as a function of the limitation of the real systems and the reduced-power devices (power adaptation in Fig. 4) [15]:

$$\begin{cases} u_{c-\mathrm{mod}} = k_v u_c \\ i_{tract-ref} = k_i i_{tract-\mathrm{mod}} \end{cases} \quad (1)$$

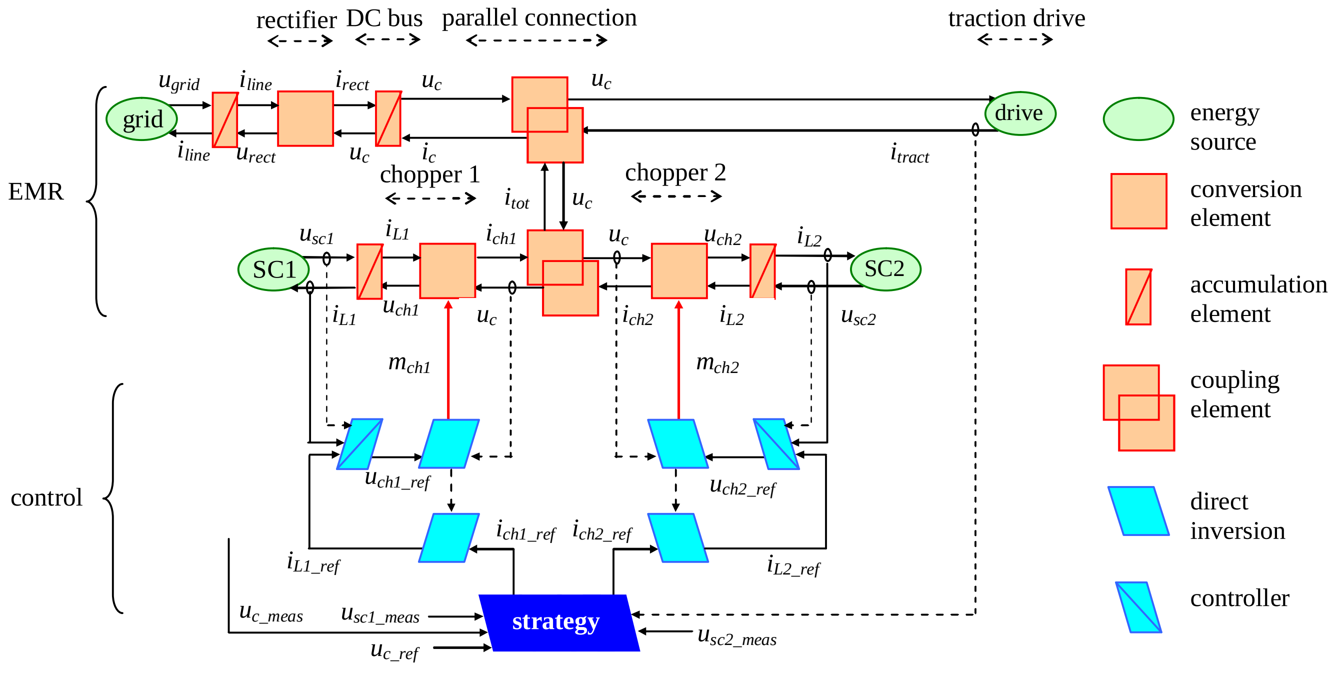

Fig. 3. EMR and inversion-based control of the new supply system

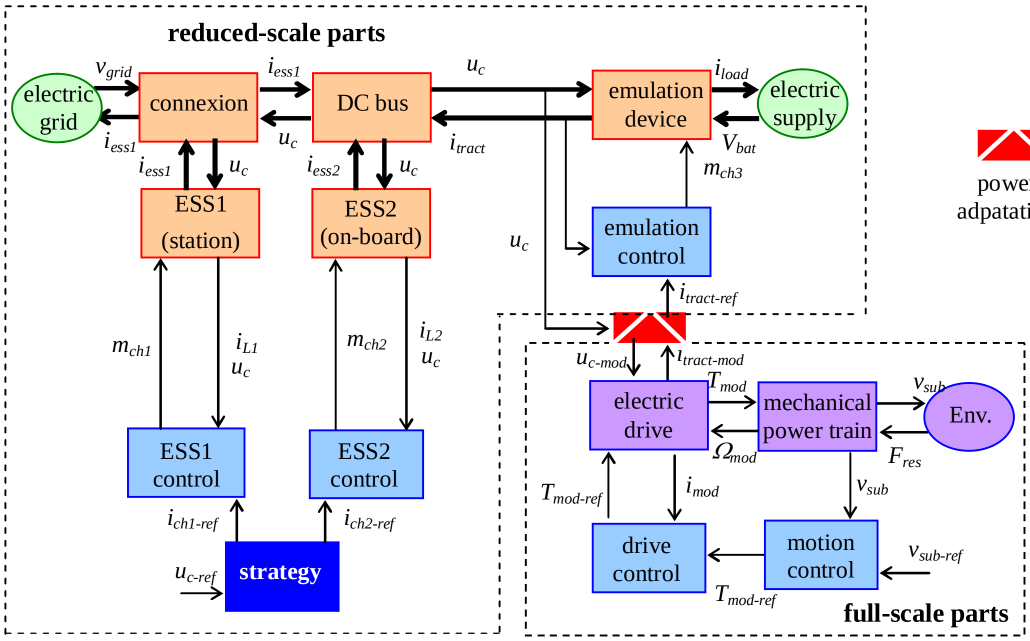

Fig. 4. HIL simulation principle of the new supply subsystem

The capacitor voltage u_c is amplified using the k_v coefficient. This model voltage $u_{c\text{-}mod}$ is imposed to the subway model, which delivers the equivalent traction current $i_{tract\text{-}mod}$ according to the action and reaction principle. This current is then decreased using the k_i coefficient in order to generate the current $i_{tract\text{-}ref}$. This reference is used by the control of the emulation chopper in order to impose the equivalent traction current in the dc bus as a function of the subway operation.

The power amplification k_p depends on the adaptation coefficients:

$$k_p = \frac{u_{c-\mathrm{mod}}\, i_{tract-\mathrm{mod}}}{u_c\, i_{tract-ref}} = \frac{k_v}{k_i} \tag{2}$$

IV. Reduced-scale Experimental Set-up

The reduced-scale experimental set-up is composed of different power devices (green and orange blocks in Fig. 4) and of different control parts (blue and purple bocks in Fig. 4).

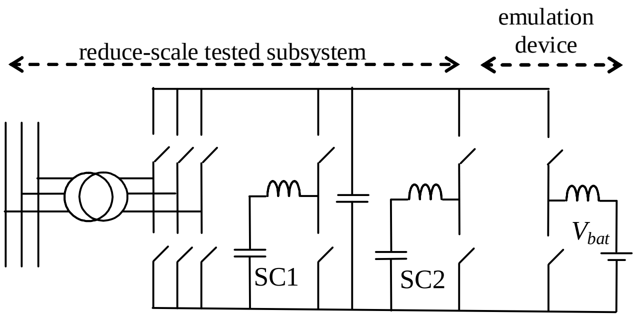

Fig. 5. Reduced-scale experimental set-up for HIL simulation

A. *Hardware devices for the HIL simulation*

The experimental set-up is composed of two power test-benches: one for the in-station ESS (with SC1), and one for the on-board ESS (with SC2) and the emulation device (Fig. 5).

Two identical supercapacitor banks (BATSCAP M2-54V130F) are used for SC1 and SC2. Each module is composed of 20 supercapacitors of 2 600 F connected in series (Fig. 7). Six IGBT voltage source inverter legs are available in each test-bench. If only 3 inverter-legs are required in the studied HIL simulation, more inverter legs can be used for HIL simulation using a real electrical traction machine [11]. Four diode rectifiers are available on each test bench. Different sensors and safety systems are also integrated. Inductors of 100 mH are used to smooth the currents in the supercapacitors.

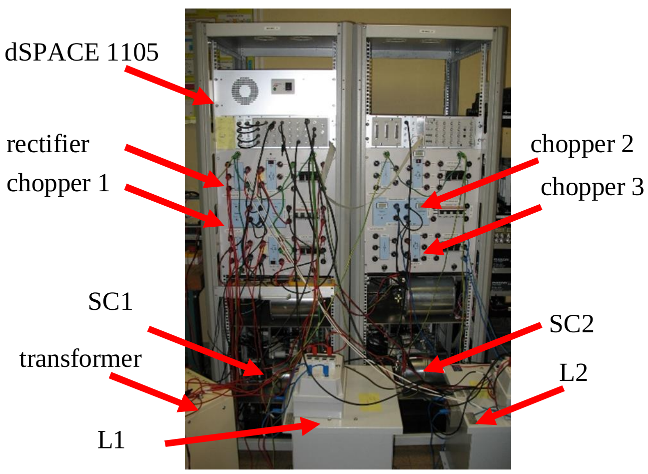

Fig. 6. Reduced-scale experimental set-up

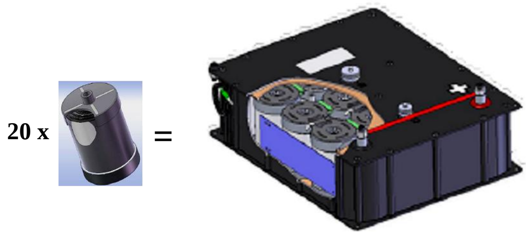

Fig. 7. BATSCAP M2-54V130F

A dSPACE© 1105 controller board is used to control the system in real time. Different interface cards have been developed to manage all signals.

B. *Software organization for the HIL simulation*

Ussualy two different controller boards can be used in HIL simulation: one for the control of the system under test and another one for the control of the emulation device and the simulation of the subway model in real time.

In this case, a single controller board is used. It contains all control parts (blue bock in Fig. 4) and model parts (purple blocks in Fig. 4).

A first part of the control program is dedicated to the measurement, the active limitation and the software Pulse Width Modulation. The associated sampling period is set to $T_{samp1}=83\mu s$. The modulation frequency is set to $f_{mod}=1.2kHz$. High values of inductors are then used to smooth current ripples in supercapacitors.

A second part of the control is dedicated to the control of the ESSs, the control of the emulation device and the simulation of the subway traction system in real time. The associated sampling period is set to $T_{samp1}=830\mu s$.

V. Experimental Results

A. *Experimental set-up validation*

First tests are achieved to validate the safe operations of the new experimental set-up. All active limitations are checked such as the dc voltage limitation, which is activated for u_c greater than 300 V (Fig. 8). The charge and discharge of both supercapacitors banks are also tested using the current loops (Fig. 9).

B. *Power transfer validation*

A first simple experimental result is provided (Fig. 10). A constant current reference for SC1 is imposed. The voltage of SC1 decreases when the voltage of SC2 increases until the maxi-mal value is reached. Because the SC1 voltage decreases (discharge of SC1), the power of SC1 decreases with a constant value. As the power is transferred from SC1 to SC2, the power through SC2 evolves inversely from that of SC1. Finally, due to the losses in the conversion scheme, the SC2 current decreases.

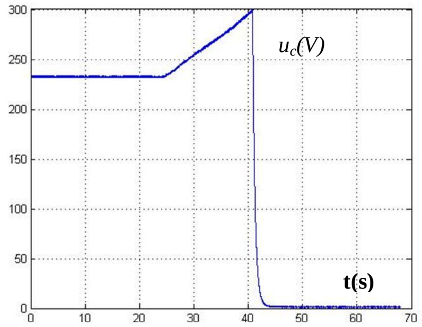

Fig. 8. Test of the active limitation of the dc bus voltage

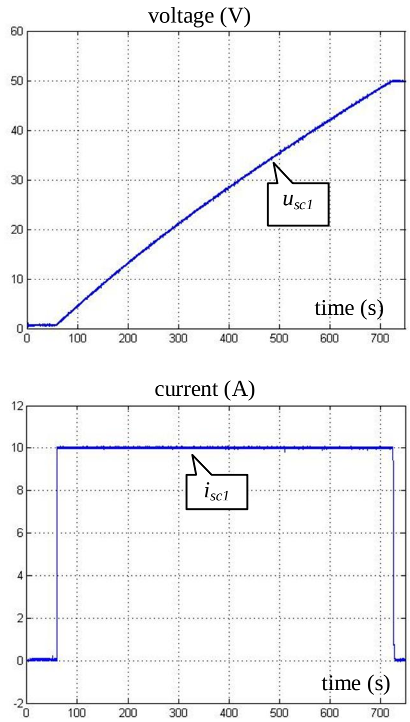

Fig. 9. Test of the charge of SC1

VI. Conclusion

A new subway traction system has been proposed using only supercapacitor to move the vehicles between two stations. The operation without supply rail between stations can significantly reduce the infrastructure cost and management. Moreover, this new topology could enable a better energy recovery during braking operations, and reduce the energy consumption of the subway. The fast charge of the on-board ESS is ensured at each station by supercapacitor banks.

A specific reduced-scale experimental set-up has been developed to validate the energy management of this new traction system in different operations. It is composed of two supercapacitors bank and power electronics. An emulation chopper is used to reproduce the traction current using a HIL simulation method. A single controller board is used to control the reduced scales ESSs, the emulation chopper and to simulate in real time the model of the subway traction subsystem. First experimental results are provided for the power transfer between supercapacitors in station.

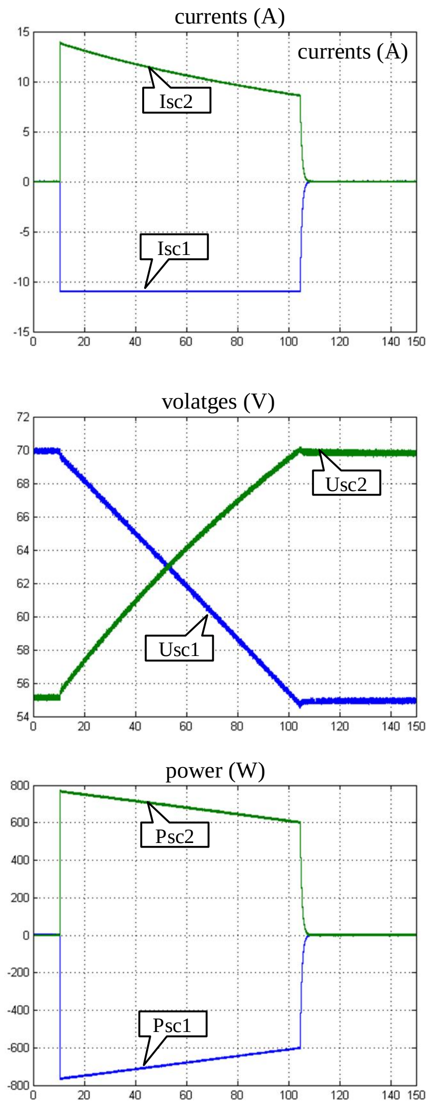

Fig. 10. Experimental results of the power transfer in station

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