An ‘on scale’ simulator for urban
DC railway traction application

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Abstract—This paper discusses on an experimental platform of an electromechanical simulator able to reproduce the power flows between a railway vehicle and the power supply system. The platform consists of an scaled-down system. It represents an urban DC railway systems in normal and extraordinary operating conditions. It is equipped with hardware and software components, suitable for testing mechanical moving, electrical traction components and systems, storage device behavior and control strategy. In the final part of the paper the short-term vision about the platform in the context of Hardware in the Loop (HIL) application is focused.

Keywords— urban DC railway power system; ‘on scale’ prototype; experimental results; testing and validation; Hardware In the Loop.

I. INTRODUCTION

Today the development of the railway systems is showing a rebirth in many parts of the world. This is due to the new trends in ecological field, clean energy production and energy efficiency. The wild opportunities to manage electrical energy aiming at reducing consumption is one of the advantages of moving person and good by electric traction, which uses electricity as primary source. Reducing energy consumption and CO₂ emissions are playing a critical role in studying and designing innovative and highly competitive transportation systems. The renewal of the electrical railway design, in terms of power component and system as well as control strategies, is widely observed (e.g. [1]). Recent studies propose the use of technological improvements, new automation facilities and management algorithms.

As a consequence of these new needs, special lines of research address in both defining innovative numerical tools and realizing experimental simulators, suitable for testing and validation. The advantages of using tools and simulators are related to the opportunity of making more simply tests for studying new emerging technologies, as well as novel system configurations, and innovative management algorithms and strategies. These facilities, when representing with accuracy the real environment of operation, reduce both cost and time of testing for innovation.

Simulators used for railway design need to model complex power systems. They have to represent: the geographical extension of the system; fixed (i.e. the infrastructure) and moving (i.e. the vehicles) parts. Simulators consist of mechanical, electrical, signals and control sections. They must be able to: accurately define the environment of interest and model the sections of system under test; analyze results for alternative operating conditions; if possible, compare numerical with real data; if necessary, refine the model.

In this context, the proposals for railway simulator are wild as well as the applications alternative (e.g. [2], [3], [4]). There are proposed various simulators in different numerical environments. It is discussed on the opportunity of using commercial-off-the-shelf (COTS) or dedicated softwares. There are addressed topics as: energy saving, renewable power source and storage device use, implementation of innovative algorithms for the management of power flows, real-time control techniques, model-based design techniques, energy efficiency.

In the context of simulation, relevant results are obtained by observing experimental tests. This means to realize hardware platforms able to represent the behavior of entire system or suitable portions of this. In the sector of railway, there is extremely expensive and very laborious to perform experimental tests on real system. Indeed, territorial extension, high power/energy implied, mechanical, electrical and signal implementations constraint the realization of new experimental platforms. Accordingly to these observations, in many cases, where a suitable set of applications is individuated, it is possible to think on ‘scaling-down’ the real system. So an ‘on scale’ experimental platform is realized. The hardware is configured to suitably replace the physical transport system, while control devices and software can be used to implement regulation strategies. In the assigned range of hypotheses, the ‘on scale’ platform is able to emulate the real system for several operating conditions, concurring to reduce the cost of experimentation, while preserving the validity of results.

This paper discusses on the experimental platform built up at the Department of Electrical Engineering and Information Technology of University of Naples. The platform represents an ‘on scale’ simulator for urban DC railway traction application. The platform was realized in a series of steps. At the present, the system consists of three main sections: mechanical, electrical and control. The mechanical section is constituted by an inertial load, which can be used to represent dynamic effects related to the motion of a heavy vehicle on a railway track. The electrical section evolved during the time. The oldest consists of an electrical drive (converter and
electrical motor), physically connected to the mechanical section. The newest part represents an AC/DC Electrical Substation and the DC traction circuit. On necessity, at the end of the traction circuit a storage device by means of a terminal DC/DC controlled converter can be connected. The control section implies control and measuring devices. A SCADA system is able to manage measurements and control variables according to the superimposed control laws.

Aims of this paper are to: i) focus on the platform details; ii) give evidence to a series of experimental tests, pointing out the platform state variables which can be measured and controlled; iii) formulate the future vision about the platform in the context of a Hardware In the Loop (HIL) application.

II. THE DESIGN OF AN URBAN 'ON SCALE' RAILWAY SIMULATOR

Any railway simulator has to represent the electromechanical behavior of vehicles in the power system, according the imposed supervisory control laws. As a consequence, any simulator consists of mechanical, electrical and control sections.

The mechanical section has to represent the main dynamic aspects related to the motion of the train mass on the track. This section has to reproduce the relation among acceleration, speed, mass and forces of the real mechanical subsystem. The aspects which have to be studied are vehicle speed, rotational speed of the traction wheels, speed of the electrical traction motor, and, eventually, skid effects. The criteria to scale down the real system to the simulator can be based on the dynamic similarity principle, leading to respect the same dynamic characteristics of the real system. This approach is able to guarantee dynamic resemblance between the real system and simulator.

The electrical section has to represent both the power system and on-board electrical drive. It mainly consists of feeder, traction circuit, on-board converter and electrical motor. Special attention has to be paid to take into account the effect of the moving load on the traction line.

The control section has to monitor and regulate system variables, according to the control strategy. The control has to manage subsystem variables, accordingly to the interaction between mechanical and electrical sections. This includes testing the system in normal conditions (i.e. start, accelerating, stopping, coasting,...) and in extraordinary conditions (communication bus fault, electric fault,...). It has to verify the functionality of the entire platform. On necessity, the control technology has to be designed for implementing advanced supervisor control algorithms.

In the following the main characteristics of the platform were detailed.

III. LABORATORY PLATFORM

The urban DC railway simulator platform was set up at the Transport Research Laboratory (TRLab) of the Department of Electrical Engineering and Information Technologies at the University Federico II of Naples [5-8]. The front view of the platform is shown in Fig.1.

This platform is an hardware implementation of the mechanical, electrical and control sections.

The sections have been chosen regarding the existing urban railway technologies used in Italy. The mechanical part, consisting in a heavy inertial load, is able to represent the dynamics of the vehicle during the different operating conditions of acceleration, cruising and braking phases. The electrical section consists of: a AC/DC power converter, two varying resistance, an electrical drive, and a DC/DC power converter. The AC/DC power converter represents an AC/DC Electrical Substation, the two varying resistance are the contact lines of the odd and even tracks. The values of the resistance can be regulated according to the position of the vehicles on the tracks. The regulation of the resistance values is related to the speed of the train. The electrical drive, physically connected to the mechanical section, represents the on-board engine. If necessary, the DC/DC power converter can be connected to the end terminal of the contact lines. It can be used to represent an alternative supply bus of a storing bus for energy recovery during braking. With reference to the control section, a supervisor manages the real time operation of the entire system controlling the interactions between the various sections. This section is realized by means of a hierarchical approach.

In the following, the main details of any sections are evidenced.

A. Mechanical section

The mechanical section is designed to reproduce an inertial load. It represents the response of a railway trolley to the applied forces. With reference to the frontal view depicted in the Fig.2, the main mechanical section consists of:

- the shaft of the electrical motor (1);
- the thooted coupling (2);
- the reduction unit, consisting of 3 gears (3,4,5);
- two coaxial hollow shafts (7,8);
- an axle with two wheels (10);
- two sets of rods (6, 9); the second one (9) connects the hollow shafts with the axle (10);
- two elastic spacers.
This section reproduces the equivalent translating mass. The wheels are proportional to the mass of the train. In order to obtain different friction forces, additional masses can be fixed on the mobile frame.

On necessity, other inertial loads completes the mechanical section. In some tests, a group equipped with a converter, an induction motor and a rotating inertia were used to reproduce a second vehicle on the track (see Fig. 3).

### Table I - Mechanical section Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent inertia $J_t,1$</td>
<td>kgm$^2$</td>
<td>3.7</td>
</tr>
<tr>
<td>Speed $\omega_{t,max}$ referred to $J_t,1$</td>
<td>Rpm</td>
<td>1500</td>
</tr>
<tr>
<td>Equivalent inertia $J_t,2$</td>
<td>kgm$^2$</td>
<td>3.25</td>
</tr>
<tr>
<td>Speed $\omega_{t,max}$ referred to $J_t,2$</td>
<td>Rpm</td>
<td>2500</td>
</tr>
<tr>
<td>Wheel Diameter</td>
<td>M</td>
<td>0.92</td>
</tr>
<tr>
<td>Transmission ratio $\tau_1$</td>
<td>-</td>
<td>4.8</td>
</tr>
<tr>
<td>Transmission ratio $\tau_2$</td>
<td>-</td>
<td>6.4</td>
</tr>
</tbody>
</table>

### Table III – Main data of the electrical section

#### Electrical line

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltage ($V_{in}$)</td>
<td>V</td>
<td>535</td>
</tr>
<tr>
<td>1st track total resistance ($R_{lin,1}$)</td>
<td>$\Omega$</td>
<td>0.1÷10</td>
</tr>
<tr>
<td>2nd track total resistance ($R_{lin,2}$)</td>
<td>$\Omega$</td>
<td>0.1÷10</td>
</tr>
<tr>
<td>Rated line rheostat current ($i_{line}$)</td>
<td>A</td>
<td>18</td>
</tr>
<tr>
<td>Representative substation internal resistance ($R_{sub}$)</td>
<td>$\Omega$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

#### Electrical drives (UNI3403)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power of 1st Induction Motor</td>
<td>kW</td>
<td>11</td>
</tr>
<tr>
<td>Rated current of 1st induction motor</td>
<td>A</td>
<td>11.4</td>
</tr>
<tr>
<td>Rated Power of 2nd Induction Motor</td>
<td>kW</td>
<td>7.5</td>
</tr>
<tr>
<td>Rated current of 2nd induction motor</td>
<td>A</td>
<td>15.6</td>
</tr>
<tr>
<td>Voltage Source Inverters dc/ac</td>
<td>kW</td>
<td>22</td>
</tr>
<tr>
<td>Input DC voltage range ($V_{dc}$)</td>
<td>V</td>
<td>380÷750</td>
</tr>
</tbody>
</table>

### Control section

With reference to the control section, the real-time operation of the entire platform involves to control and coordinate the interactions between the sections. The controller is realized by means of a hierarchical approach. To achieve this requirement, it has been provided the use of a supervisor system that has the function of generating the reference values to the various subsystem controllers. Accordingly, each controller generates the references to regulate the state of own actuators.

The supervisor synchronizes the events that describe the behavior of all the system's components. The supervisor is realized by means of a main PC, with two Digital Signal Processor (DSP) boards operating through a high level of logical strategy implemented in a Matlab environment. It interrogates the various subsystems and, on the basis of data received from anyone of these, processes the signals and determines the digital signals for applying logics such as starting, cruising and stopping. The controller is also able to manage the state of the charge of the storage device eventually connected at the end of the track. The control unit consists of two DSP boards. The first one controls the electrical drive, the second one can be used to manage of storage unit.

In the following fig. 4, the scheme of the mechanical, electrical, measurement and control sections of the platform are reported. The black lines represent the electrical elements, the red lines evidence measurements and control variables. The DN block represents the power source. It is the distribution network where the railway system is connected to.

### D. Experimental results

The platform was used for a series of tests. In particular, to give evidence to the behavior of the railway simulator and point out the main variables monitored and under control, in the following there are reported the results of one relevant case study [10]. The aim of the proposal is to evidence the behavior of the platform and to verify the opportunity to use a storage device for reduce substation current peaks and recharge energy during braking periods.
The case study is related to the simulation of the presence of two railway vehicles on the tracks for a simulation time of 60 s (the travelled spatial distance is about 570 m). For any vehicle a running service is assigned. The running services can be characterized by the relevant phases of: stop, acceleration, coasting and braking. The electrical section is equipped with a storage device at the end on the traction track. The storage unit is based on the LiC technology.

Fig. 4 – Detailed scheme of the laboratory platform

In the results of the test reported in the following, it is imposed that the two vehicles have two different running services. In particular, the speed cycles of the two vehicles are reported in the Fig. 5 (a). The speed cycles are input assigned. The 1st vehicle starts at \( t=0 \) and increases its speed for an acceleration time of \( 24 \) s up to the maximum speed \( v_{t,1}=65 \) km/h. This value corresponds to a motor speed \( \omega_{m,1}=1250 \) rpm. After the acceleration time, a cruise period of \( 11 \) s is imposed and, finally, at \( t=35 \) s a braking period of about \( 16 \) s is observed. The 2nd vehicle is assumed to run in the opposite direction of vehicle #1. This vehicle starts at \( t=13 \) s, accelerates to reach \( v_{t,2}=62.5 \) km/h (corresponding to a motor speed \( \omega_{m,2}=1500 \) rpm) in about \( 12 \) s, has a coasting phase of about \( 22 \) s and finally starts a braking phase which is able to stop the vehicle at \( t=55 \) s, corresponding to a braking period of about \( 10 \) s.

According to the speed waveforms reported in the Fig. 5(a), the motor torques can be observed (see Fig. 5(b)). Traction efforts waveforms are strongly related to the impose running services. Their values depend on the imposed control laws. In particular, during the acceleration periods, the two active efforts are set to the constant values of \( 340 \) N for vehicle #1 and \( 140 \) N for vehicle #2 (corresponding to a motor torque of \( T_{m,1}=47 \) Nm and \( T_{m,2}=20.2 \) Nm for the 1st and the 2nd vehicles respectively). During the braking periods traction efforts and motor torques are negative. In this case, they assume approximately the values of \(-348\) N for vehicle #1 and \(-102\) N for vehicle #2.

With reference to the state of the electrical section, voltages and currents were measured in the bus of interest. In particular, the supplied current are measured at both the substation and storage system, whereas the load currents are measured on the electrical loads. As expected, vehicle currents increase during the acceleration, as related to the increasing of the speeds. Their maximum values can be observed when the maximum speeds are reached. In the following Fig. 6(a), the measured currents are reported. The figure gives evidence to: the substation current (i.e. \( i_{sub} \)); the storage device current (i.e. \( i_{sto} \)) and, for sake of simplicity, the waveform of the total load (i.e. \( i_{t,1} + i_{t,2} \)) are reported. Due to the presence of the storage system, the total load current can be supplied by the substation bus and the storage device bus. As expected noting the current waveforms, the results point out specially the action of the storage system to reduce the substation current peaks. In particular, at \( t=23.3 \) s, the sum of the vehicles currents reaches its peak value 26.6 A. The storage device current is able to concur to supply a current of 8.1 A, reducing the substation contribution to the value of 18.5 A. The “peak shaving” action provided by the storage system is therefore most evident, reducing the substation current peak of 30.4%. In absence of the storage system, all the load current peak would be supplied by the substation bus. Moreover, during the braking periods, the kinetic energies can be converted into electrical energy by the electrical traction drives, as long as \( i_{t,1} + i_{t,2} \) is negative. More specifically the maximum regenerated vehicle current occurs when the 1st vehicle begins to brake (\( t=35 \) s). In this time \( i_{sto} \) reaches the maximum regenerating current of about 9.8 A. This means that the contribution of LiC is linked to the power requirements of the mechanical drives, limiting effectively the power drawn by the main supply.
The beneficial action of the storage system can be observed also on the voltage waveforms. The line voltage drops smoothing action carried out by the stationary LiC ESS, is clearly highlighted in Fig.6(b), which displays the line voltages of both the vehicles $V_{t,1}$ and $V_{t,2}$, as well as the storage voltage $V_{sto}$, at the line point where the ESS is placed. The impact of the storage system on the main electrical substation is shown by the decreasing of the 1st line voltage drop ($\Delta V = 79$ V at $t = 23.3$ s) compared to the case of total dissipative electrical braking on the ballast resistor, where the same line voltage drop reached about 21.5 % of the line no-load voltage ($V_{sub,0} = 535$ V). Furthermore, also the overvoltage during the braking phases is excellently reduced because the regenerated energy is stored in the ESS. Finally, due to the presence of the stationary energy storage system an energy saving of about 14.9 % is calculated.

IV. FUTURE VISION ABOUT THE PLATFORM

The simulator platform set up at the Transport Research Laboratory (TRLab) of the Department of Electrical Engineering and Information Technologies at the University Federico II of Naples is a reliable tool to test components and systems in railway application. It can be used for testing the action of both new components as well as novel control strategies. In this context, the effectiveness of new storing technologies and innovative algorithms expressively oriented to the reduction of consumption and efficient energy management was already widely evaluated. Tests were addressed to compare solutions for on-board and on-line application, while changing system structure and operating conditions.

Today, it is foreseen to extend the vision about the platform. For the next short term, the aim is addressed toward the implementation of a Hardware-In-the-Loop (HIL) simulator for metro and light rail urban application.

HIL is a technique that tests devices (i.e. the Hardware) by adding the complexity of the plant where devices is connected to, thought the mathematical representation of all related systems (i.e. the Loop). Today HIL is a consolidated testing platform which can be useful for a large variety of experimental study and application as high performance simulator.

Our vision arises as a direct evolution of the traditional HIL techniques, which are oriented to test new control units in laboratory desk able to reproduce the system where they are addressed. The platform will represent the ‘Hardware’ in the simulated environment of the supply distribution network (i.e. ‘Loop’). Sensors and actuators of the platform will act as the interface between the hardware and the simulated distribution network. The instantaneous value of each sensor of the platform will be controlled by the network, so that output actuator control signals will be accordingly generated.

In this context, also extreme conditions for the hardware as well the loop will be simulated, thus evaluating the behavior of components and control algorithms also during fault-tolerance conditions or automatic repetitive tests.

This new vision in using the platform as the hardware in the distribution network loop is related to the evidence that metro and light rail systems are today recognized as an essential instrument for setting up a new urban development and sustainable mobility paradigm. Clearly, this implies that the interactions between the distribution and traction systems as well as the efficient management of the energy flows between the systems will be key points. It is widely observed that there is a joint responsibility for public transport authorities and operators to increase their commitment to energy-efficiency and lowering emissions. The rationalization of electric consumption and energy savings of the transportation system in an urban context involves hard-working operating conditions for the existing electrical supply networks. Today, the increase in both rolling stock power and number of vehicles operating on tracks stresses the distribution network in terms of power losses and voltage drops. Moreover, the recovery of the breaking kinetic energy can attain functions such as voltage stabilization in weak distribution networks, operation without overhead lines.

Employing the HIL paradigm will also permit to test the platform in the upgraded distribution environment of Smart Grid application. In such a context, the effectiveness of RESs (Renewable Energy Sources) and DERs (Distributed Energy Resources) connected in the distribution network busses supplying railway systems can be evaluated. As well as, the opportunity of considering the railway system as a large network of distributed load/generation buses can be evaluated in the future.

In such a way, the HIL will realize a powerful energy system test-facility where innovative market oriented control strategies can be developed according to the territorial context. The HIL simulator may be also used in defining contractual relationship
between energy suppliers and railway systems, including the
definition of real practice and procedures.

V. CONCLUSIONS

The integration, test and verification of modern railway
systems represent a serious challenge. Because of the risks
involved, it is not conceivable to integrate new technologies
and control strategies with direct subsystem interconnection,
without making an intensive campaign of preventive tests on
the system behavior. Thus, nowadays, numerical simulation
technology and laboratory experimental setup are widely used
in the railway sector.

Although many types of simulation software and platforms
have been established for railway industry, the new trend
addresses to virtual development platform which are
multifunction and can suitable support the target based design
and optimization of an entire traction system effectively.

In this context, the paper investigated on the experimental
platform set up at the University of Naples and its opportunity
of extend, according to the new trends of research. In this case,
the platform would be considerate as a simple section of a
whole simulator (Hardware in the Loop-HIL), suitable to
represent a portion of network in a urban context. So that, the
platform could be used to test, with real hardware scaled down
parts, the effect of a transport system in a urban distribution
context. Aims could be related to: determine new requirements
for the railway network’s infrastructure; analyze the capacity of
lines and stations; analyze the robustness of timetables (by
means of repetitive automatic tests); calculate power and
energy consumption related to imposed train services. If
suitably upgraded, the platform may be also effectively used to
test the interaction between the distribution network and the
railway system in the context of energy market strategies.

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VII. REFERENCES


