Abstract—In the paper is presented an auxiliary substation equipped with battery based energy storage system ( Auxiliary Battery Substation - ABS) and the benefits for railway applications are shown. The proposed solution is able to reduce the effect of the peak current and voltage drops on weak traditional 3 kV feeding line during high performance trains traction. The ABS also increase the system efficiency by recovering energy during train braking phase and making it available again at the next starting time, minimizing the energy required to the main substation. An extensive simulation framework is performed on a real Italian 3 kV DC railway system feeding a new generation high speed train where the ABS supports conventional supply system. The simulation results confirm the effectiveness of the ABS in terms of peak current reduction and voltage drops compensation. Finally, The ABS allows reducing losses and increasing the energy saving in the railway feeding line.

Keywords—battery storage system, energy saving, railway system simulation, regenerative braking, voltage drop.

I. INTRODUCTION

The heavy impact in terms of pollution and meaningful contribution to the whole energy consumption is leading to a radical change in transportation systems [1]. This irreversible trend is also affecting the electrified transport systems, already characterized by lower consumptions and emissions compared to road transport. The current technological trend suggests the use of trains characterized by higher and higher performance and consumption, able to transport more and more people (high capacity) in an ever more fast way (high speed) and in safer way [2]. For this reason efficiency and energy savings became a priority not only for the railway sector, but also for the electrical system connected to it. The widespread penetration of high speed/high capacity (HS/HC) trains on 3 kV existing DC lines has a considerable impact on the voltage drop and power consumption of railway systems, especially for one side supplied contact line fed by conventional electric substation [3], [4]. Therefore, it is necessary to study design criteria and technological solutions able to improve the overall system efficiency and to recover the trains’ braking energy.

The attention is focused in particular to improve the feeding lines performances, reducing the negative impact on the distribution or sub-transmission networks by an optimized use of the energy and by recovering braking energy from circulating trains. In a conventional railway system equipped with irreversible DC substations, braking energy is only usable if other trains are simultaneously demanding energy, otherwise, it would be wasted as heat on the vehicles braking resistors. Considering the traffic density, this desired condition is however very difficult to achieve in the traditional railway lines, on the contrary to what happens in the metro networks [5]. Better use of the braking energy can be achieved by using an auxiliary battery substation (ABS) installed along the track as additional or boost substation. The ABS is realized with electrochemical storage able to provide the difference in power required at the vehicle starting and recharge itself by the vehicle braking energy.

Large capacity, long life, and rapid charge/discharge characteristics are necessary for applying actual energy storage system in railway [6]. Many tests on the recent lithium-ion battery systems are made to evaluate the real working condition of the energy storage systems and to optimize design criteria [7], [8]. New technologies and control algorithms are developed during the recent past years for making stationary energy storage system applicable to DC electrified railway systems solving the issues related to life cycle, efficiency, maintenance [9], [10].

In technical and scientific literature only a few works dealing with the energy storage systems to support 3 kV railway systems, focusing mainly the efficiency aspects of the problem and not the capacity extension of the track [6]. Research activities about energy storage in the railway systems is mainly focused on metro and light rail networks [11], [12]. Many studies and installation proposals go back to many years ago: in 1990 West Berlin public transport company began feasibility studies to equip the subway network with 1 MW lead acid battery (BVG) [13]. The goal was cover the peak loads arising by simultaneous acceleration of several trains using the energy stored in the battery modules. This solution enables BVG to reduce also the size of future rectifiers. Regarding light railway systems, several papers propose supercapacitor based storage systems in DC metro networks, suggesting optimization algorithms for the siting and sizing along the track [14]. In [15], the authors describe main criteria to design and control a supercapacitor substation for the compensation of voltage drops in metro networks.

This paper proposes and evaluates the performances of an ABS on a 3 kV Italian railway system, taking into account: i) track topology - slopes and curves – ii) the electrical features of the feeding line, iii) the mechanical characteristics of the vehicle and its timetable. The paper is organised as follow: Section II describes the ABS and the benefits introduced on the
railway feeding line. In Section III, kinematic of the vehicle and the railway network models used for the implementation of the calculation code are described, whereas case study and results of several simulations are presented and discussed in Section IV. Finally, conclusions are listed in Section V.

II. AUXILIARY BATTERY BASED SUBSTATION FOR ENERGY SAVING IN RAILWAY SYSTEMS

Research activities concerning technical issues related to the auxiliary battery substation such as sizing of storage system, design of the bidirectional DC/DC converter, and its control algorithm is carrying out within the S.E.R.E.N.A. research project (Smart Energy systems for Railways Efficient Networks). The project proposes an innovative solution based on ABS able to host trains having a starting power higher than line and substation capacity. The ABS sustains the current peaks absorbed during the starting time by high performance trains, such as HS/HC train operating on traditional 3 kV rail networks. Furthermore, increasing the rated current results in an increase of the line losses and voltage drops. The batteries are charged during the regenerative breaking phase and during the off-peak period; the recovered energy is used for the next traction phase of the HS/HC train, minimizing the use of energy coming from the grid. The installation of an auxiliary battery substation, in stand-alone configuration or in support to the main one, allow solving this problem and obtaining the following benefits:

- increase the number of stations served by high-speed train, with obvious benefits in terms of energy efficiency and CO₂ reduction;
- increase the interoperability;
- reduce the effect of peak current and voltage drops on the feeding line while circulating high performances trains;
- increase the energy efficiency of the system recovering energy during braking phase while the trains are approaching to the station and supporting the substation during subsequent acceleration of the train.

Actually, there are no ABS commercial applications for 3 kV railways line. The only applications, concerning mitigation of renewable energy on electrical distribution networks (e.g. SAFT system based on 2 MW lithium ion battery and installed in an Enel Distribuzione MT/BT electrical substation), or urban and rural areas network support (e.g. Customer-Led Network Revolution, a three-year project for the development of an intelligent electricity network in the UK) [16], [17]. Some electric energy storage systems were already installed in Japan, in 1.5 kV DC feeding lines, mainly to compensate voltage drops and to recover braking energy. As an example, is reported the lithium-ion based storage system at SHIN-HIKITA substation of JR West (West Japan Railway Company) installed in 2006 for the voltage drops compensation in catenary system [18]. In East Japan Railway Company, a lithium battery system was installed at HAJIJIMA substation on the Ome line and started operation on February 20th, 2013. It is the first application of the energy storage system mainly not for voltage drop compensation but for regenerative energy utilization [18].

The application of ABS storage systems could minimize invasive actions and the necessary adjustments to the feeding line, both for technical and economic aspects related to the implementation costs. Fig. 1 shows a basic electric diagram of the auxiliary battery substation [5]: the ABS can be directly connected to the traction power supply system or to the substation's busbar by means of the connection unit, which consists in the disconnector, the high-speed DC circuit breaker and the pre-charging unit. The connection between the linking unit and the actual storage unit is made by the DC/DC converter, which functions as a step-up/step-down converter [19]. The chopper system has a bi-directional function. It works as a step-down converter to decrease voltage when it charges up the batteries and as a step-up converter to increase voltage when it discharges them [5].

III. MODELLING OF THE RAILWAY SYSTEM

The proposed model is obtained by the integration of three different sub-models: railway vehicle and its kinematics, ABS, and the conventional feeding system.

A. Vehicle

The longitudinal dynamic of vehicles evolves according to the force balance equation described by the model expressed by:

\[
\frac{m_p}{dt} = F - R_{BASE}(v) - R_{LINE}(x) \\
\frac{v}{dt} = a(x)
\]

(1)

where \( m \) is the mass of the vehicle, \( \rho \) is a correction factor taking into account the rotating mass, \( v \) and \( x \) are the train speed and position respectively, \( F \) is the traction (if positive) or braking (if negative) force, which is lower and upper bounded [12], \( R_{BASE}(v) \) is the basic resistance including roll resistance and air resistance, and \( R_{LINE}(x) \) is the line resistance caused by track slopes and curves, and they are expressed by:

\[
R_{BASE} = m(\alpha_1 + \alpha_2 v^2) \\
R_{LINE} = mg \sin(\gamma(x)) + mg - \frac{a}{r(x)} - b
\]

(2)

In (2) \( \alpha_1 \) and \( \alpha_2 \) depend on the train characteristics and the train speed, and can be calculated by the train data or obtained by literature; \( g \) is the gravitational acceleration and \( \gamma(x) \) is the slope grade. Second term of \( R_{LINE} \) is the curve resistance given by empirical formulas, as the Von Röckl’s formula, where \( r(x) \) is curvature radius, and \( a, b \) are coefficients which depend on
the track gauge; in the paper the used are \(a=0.65\) m and \(b=55\) m, [20]. Trains are modelled as ideal current sources absorbing power at the accelerating time and generating power at the regenerative breaking time. The power at the wheels required to overcome the vehicle inertia, slopes and curves, aerodynamic friction, and rolling friction, is calculated starting from a given speed cycle. Going upstream the vehicle components and their related efficiencies, the power requested from the electrical substations and the current absorbed are determined by the following equation:

\[
P_{\text{VEHICLE}} = \left( m \frac{dv}{dt} + F_v \right) \eta_g \eta_m \eta_f + P_{\text{AUX\_SERVICES}} \quad (3)
\]

\[
I_{\text{VEHICLE}} = \frac{P_{\text{VEHICLE}}}{V_{\text{LINE}}}.
\]

In \(3)\), \(P_{\text{AUX\_SERVICES}}\) is the power absorbed by board auxiliary services (lighting, cooling or heating), \(m\) is the total mass of the train - including the passengers -, \(v\) is the vehicle speed, \(\eta_g\), \(\eta_m\), and \(\eta_f\) represent, respectively, the gear box efficiency, the motor efficiency and the inverter efficiency. \(F_v\) is total resistive forces, computed as sum of two terms: the basic resistance \(R_{\text{BASE}}\), and the line resistance \(R_{\text{LINE}}\), defined in \(2)\). To bring into account that the voltage along the track is not constant, the railway vehicle is modelled as an ideal current generator \(I_{\text{VEHICLE}}\), whose value is calculated as the ratio between vehicle power and line voltage \(V_{\text{LINE}}, (3)\).

**B. Auxiliary battery substation**

The ABS electrical model includes the battery modules, the DC/DC converter and the power flow controller (Fig. 2a). During the charging period, ABS receives the regenerative power from the vehicles and during the starting time, delivering power to the trains: therefore, the ABS is modelled as ideal current sources, whereas a simple constant resistor models the power converter. The DC/DC converter charges or discharges the battery modules, using an energy management strategy, according to the value of line voltage, line voltage variation and the batteries state of charge (SoC). In Fig. 2b is shown the first-order equivalent circuit of battery modules consisting in four elements [21]. The ideal voltage source represents the open circuit voltage (OCV), which is affected by battery SoC; the series resistor \(R_m\) represents internal resistance, \(r_d\) and \(C_d\) are the RC parallel circuit describing the charge transfer and double layer capacity, respectively. In \(4)\) the four main equations describing the electrical model of the battery is shown. Specifically, the first equation represents the Kirchhoff's voltage law, whereas the second one is the \(n\)-polynomial relation between OCV and SoC. The third equation models the SoC update law, according to the current drawn from the battery module, and finally the differential equation describing the RC parallel circuit.

\[
V_{\text{batt}}(t + dT) = OCV(t) - R_m I_{\text{batt}}(t) - u_d(t + dT)
\]

\[
OCV(\text{SoC}) = a_0 \text{SoC}^n + a_1 \text{SoC}^{n-1} + \ldots + a_0
\]

\[
\text{SoC}(t + dT) = \text{SoC}(t) + \frac{V_{\text{batt}}(t + dT) I_{\text{batt}}(t) dT}{3600 C_{\text{batt}}}
\]

\[
u_d(t + dT) + r_d C_d \frac{\left(u(t+dT)-u(t)\right)}{dT} = \begin{cases} r_d I_{\text{batt}}(t) & \text{if } t \neq t_k \\ 0 & \text{if } t = t_k \end{cases}
\]

where \(u_d(t)\) is the \(r_d C_d\) parallel circuit voltage, \(dT\) is the time step, the \(a_0 \ldots a_n\) are interpolation coefficients and \(C_{\text{batt}} [\text{kWh}]\) is the ABS capacity.

**C. DC feeding system**

Conventional substations are represented by ideal DC voltage sources, series resistance and series diode only if the substation is not reversible [7], [11]. The contact wire is modelled as a set of electric resistances that change their value according to the vehicle position. If \(x(kdT)\) is the train position at the time \(kdT\), the value of the resistance upstream \(R_a\) and downstream \(R_b\) to the vehicle towards a generic node of the railway feeding system (conventional substation, ABS or another train) are calculated by:

\[
\begin{align*}
R_a &= r x(kdT) \\
R_b &= r[d - x(kdT)]
\end{align*}
\]

where, \(R_a\) and \(R_b\) are expressed in [\(\Omega\)], \(r [\Omega/\text{km}]\) represents the resistive coefficient, \(d [\text{km}]\) is the distance between the two nodes - upstream and downstream the train - , and \(x(kdT) [\text{km}]\)
is the distance between the train and the upstream node at the
each time step $kdT$. Finally, the electric model of the overall
railway system, one side supplied contact line, is shown in
Fig. 3. Furthermore, it is necessary to improve the train electric
model with some small capacitances in parallel to the vehicles
in order to describe the receptivity of the network under
regenerative braking conditions [15]. They model the voltage rise along the contact wire during the first phase of the
regenerative breaking that is used by the ABS control to detect
the availability of breaking energy along the track.

IV. SIMULATION FRAMEWORK

The railway system model was implemented in a rail
simulator based on the ‘quasi static’ backwards looking
method, due to its short simulation times for estimating energy
consumption of vehicles following an imposed speed cycle
[14], [15]. The power needed to satisfy the speed cycle is
determined at the wheel level. Then, the power provided by the
feeding line is estimated by means of efficiency of each
electrical/mechanical components of the power train. Several
simulations are carried out in which one HS/HC train moves in
the two opposite directions following the same driving cycle.

A. Case study

The effectiveness of the proposed ABS is verified on the
railway line linking Roma Termini railway station to the
international airport Leonardo da Vinci. At present, two
different types of train provide the service: a direct train
(Leonardo Express – maximum power 2800 kW) leaving from
Roma Termini station every 30 minutes, and a high traffic train
(maximum power 3500 kW) leaving from Roma Tiburtina
station every 15 minutes. In particular, the tests are performed
on the route section MAGLIANA–FIUMICINO (15.8 km long
and shown in Fig. 5a) of the ROMA TERMINI–FIUMICINO
railway line.

The DC line consists in a 3 kV one side supplied contact
line fed by one conventional (not reversible) electric substation,
located in Magliana, and by a li-ion ABS assumed by the
Authors, at Fiumicino station. It is considered only one vehicle
moving along the track having ETR 1000 electrical and
mechanical characteristics. Driving cycle consist in a starting
phase, followed by a stretch of line path at constant speed
depending on the speed limit along the track, and finally ending
with the braking phase. Driving cycle and track elevation are
shown in Fig. 5b. The maximum speed that the train can reach
on a stretch of the path is highlighted in dotted black line and
its maximum value is 125 km/h. ETR 1000 train and DC
feeding line are characterized by the parameters listed in Table
I and Table II, respectively, whereas in Table III are reported
the electrical features related to the ABS assumed on the track.

![Fig. 5a. Railway line MAGLIANA–FIUMICINO - Google Earth view.](image)

![Fig. 5b. ETR 1000 drive cycle and track elevation on the line MAGLIANA–FIUMICINO.](image)

**TABLE I. ETR 1000 PARAMETERS**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net weight [t]</td>
<td>447</td>
</tr>
<tr>
<td>Loaded weight [t]</td>
<td>500</td>
</tr>
<tr>
<td>Max. traction power [kW]</td>
<td>9800</td>
</tr>
<tr>
<td>Max. train speed [km/h]</td>
<td>400</td>
</tr>
<tr>
<td>Accessories power [kW]</td>
<td>1000</td>
</tr>
<tr>
<td>Coefficient of auxiliary use</td>
<td>0.75</td>
</tr>
<tr>
<td>Power train overall efficiency</td>
<td>0.86</td>
</tr>
</tbody>
</table>

**TABLE II. TRACK ELECTRIC PARAMETERS**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track’s length [km]</td>
<td>15.8</td>
</tr>
<tr>
<td>Rail electric resistance [Ω/km]</td>
<td>0.062</td>
</tr>
<tr>
<td>Substation max. power [MW]</td>
<td>5.4</td>
</tr>
<tr>
<td>Substation DC voltage [V]</td>
<td>3000</td>
</tr>
<tr>
<td>Substation internal resistance [Ω]</td>
<td>0.013</td>
</tr>
<tr>
<td>Maximum line voltage [V] (+20% - CEI EN 50163)</td>
<td>3600</td>
</tr>
<tr>
<td>Minimum line voltage [V] (+33% - CEI EN 50163)</td>
<td>2000</td>
</tr>
</tbody>
</table>

**TABLE III. ABS ELECTRIC PARAMETERS**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery technology</td>
<td>Li-ion</td>
</tr>
<tr>
<td>Maximum power [kW]</td>
<td>2000</td>
</tr>
<tr>
<td>Nominal capacity [kWh]</td>
<td>500</td>
</tr>
<tr>
<td>ABS DC voltage [V]</td>
<td>2000</td>
</tr>
<tr>
<td>Maximum SoC value [%]</td>
<td>90</td>
</tr>
<tr>
<td>Minimum SoC value [%]</td>
<td>30</td>
</tr>
</tbody>
</table>
B. Numerical results

Several simulations are carried out both to evaluate the impact on 3 kV DC supply system of a HS/HC train as an ETR 1000, and to evaluate the benefits introduced by the proposed ABS defining its power and energy specifications. In particular, Fig. 6a and Fig. 6b show the actual traffic conditions and the expected traffic conditions on the railway test line adding one HS/HC train, every 30 minutes to the existing transport service. The actual conditions and the impact in terms of voltage drop, evaluated with the calculation code RECUPERA [22], on the feeding line due to an ETR 1000 train is shown in Fig 7a and Fig. 7b, respectively. The average useful voltage on the DC line, adding to the existing service one ETR 1000 train is significantly reduced compared to the voltage value without high performances train and is not enough to reliably manage the railway line. In particular, the line voltage reaches almost 1700 volts, a value well below the minimum allowed. Table IV shows the expected average useful voltage on the feeding line by limiting the current absorbed by the ETR 1000. As expected, reducing the current draw from the feeding line by the ETR 1000, therefore penalizing its performance, results in a rising value of the average useful line voltage. It is worth to note that the difference in train travel times limiting its traction current at 2400 A and 1330 A, respectively, is less than one minute.

<table>
<thead>
<tr>
<th>ETR 1000</th>
<th>LIMITED CURRENT [A]</th>
<th>AVERAGE USEFUL LINE VOLTAGE [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO - ETR 1000</td>
<td>3147</td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>2886</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>2911</td>
<td></td>
</tr>
<tr>
<td>1330</td>
<td>3050</td>
<td></td>
</tr>
</tbody>
</table>

Table V reports the comparison, in terms of losses and energy supplied by the conventional substation, with and without ABS on the track, respectively. Using the proposed ABS, a slight reduction in losses is obtained when the train moves from the station corresponding to conventional substation, and much better results moving the train in the opposite direction.

<table>
<thead>
<tr>
<th>STORAGE</th>
<th>LOSS [%]</th>
<th>IMPROVEMENT</th>
<th>VALUE</th>
<th>IMPROVEMENT</th>
<th>SUPPLIED ENERGY [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO ABS</td>
<td>13.77</td>
<td>-</td>
<td>363.63</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>8.51</td>
<td>-5.26</td>
<td>232.71</td>
<td>-130.92</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8 shows the line voltage trend without ABS and with ABS on the track and circulating only one ETR 1000 on the line MAGLIANA-FIUMICINO. Without ABS supporting the main electrical substation, line voltage reaches a minimum value approximately equal to 1949 V while the train is running on the track. The auxiliary substation, reducing the voltage drop of about 22%, allows to limit the line voltage variation according to the standard CEI EN 50163 and to avoid that the main
The paper shows the benefits introduced by a battery based auxiliary station on weak railway supply system, circulating a high-performance train on the track. The electrical models of railway supply system, train and ABS are described and a simulation tool is implemented to quantify the power flow on the feeding line. The test are performed on a real Italian 3 kV railway system in which circulates one ETR 1000, the new HS/HC train of Ferrovie dello Stato Italiane. Preliminary results show that an ETR 1000 on the existing line without current limitation leads to voltage drops not admissible by the standard CEI to reliably manage the railway line. The simulation results shown that an ABS is able to fully support the existing supply system making no need to limit the absorbed peak current from the HS/HC train or to enhance the main substation. Furthermore, the more stabilized line voltage and the significant reduction of the peak current (43.2%) supplied by the main substation, results in a consequently reduction of the voltage drops and losses of 5.26% and 22.4%, respectively.

V. CONCLUSIONS

The paper shows the benefits introduced by a battery based auxiliary station on weak railway supply system, circulating a high-performance train on the track. The electrical models of railway supply system, train and ABS are described and a simulation tool is implemented to quantify the power flow on the feeding line. The test are performed on a real Italian 3 kV railway system in which circulates one ETR 1000, the new HS/HC train of Ferrovie dello Stato Italiane. Preliminary results show that an ETR 1000 on the existing line without current limitation leads to voltage drops not admissible by the standard CEI to reliably manage the railway line. The simulation results shown that an ABS is able to fully support the existing supply system making no need to limit the absorbed peak current from the HS/HC train or to enhance the main substation. Furthermore, the more stabilized line voltage and the significant reduction of the peak current (43.2%) supplied by the main substation, results in a consequently reduction of the voltage drops and losses of 5.26% and 22.4%, respectively.

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