Smart Electrical Infrastructure for AC-Fed Railways with Neutral Zones

Eduardo Pilo, Member, IEEE, Sudip K. Mazumder, Senior Member, IEEE, Ignacio González-Franco

Abstract—This paper presents a proposal to modify power supply systems currently used in AC-fed railways with neutral zones in order to allow power-flow routing. The proposed system complements the existing infrastructure with additional power-electronic devices connected in parallel to both sides of the neutral zones, allowing control of power flow through adjacent electrical sections. Description and control of such a modified railway system is outlined in this paper. Also, a mixed integer programming (MIP) optimization problem is formulated which minimizes the investment and the operation costs, while ensuring the power supply to the train traffic. This optimization model is used to allow a systematic evaluation of the benefits of implementing such a railway smart grid system. Finally, a section of the high-speed line Madrid-Barcelona is used as a case study and the advantages of the proposed system are quantified in two different scenarios.

Index Terms—Power system, smart grid, controllability, railway, management, planning, energy management, optimization, efficiency.

I. INTRODUCTION

ELECTRIFIED railways are normally considered one of the most energy-efficient modes of transport, especially over economically-viable operating distances. One of the key factors for this higher efficiency is the interconnections of the trains via the catenary (or active rails in some cases), which allow trains to perform regenerative braking. In other words, a train equipped with regenerative braking device, while undergoing deceleration due to braking, is able to act like a generator by efficiently feeding part or all of its kinetic energy in the form of electrical power to the traction electrical grid. For that reason, in the last two decades, research has focused on increasing the efficacy of the onboard regenerative braking systems by (i) enhancing the efficiency and the flexibility of the onboard electronic converters [1]-[3], (ii) optimizing the operation, for instance, by designing the train schedules or the driving to maximize the energy recovery [4], and (iii) enhancing the ability of the infrastructure to deal with excesses of power, for instance, by using energy-storage devices and reversible substations in DC system.

The development of electrical smart grids is producing technologies that allow a rich interaction between the agents of the overall system (e.g., utilities, consumers, small generator, etc.) based on active management of the demand and the generation and active control of the electrical networks [5]-[7]. Although railways electrical grids are a particular case of electrical grid, some of their characteristics make them unique. First of all, the loads vary spatiotemporally because the locations of the trains and their power demands vary on almost a continual basis. Further, the number of loads is relatively small even though their load demand can be high. In addition, the loads are somewhat predictable because the nominal schedules of the trains are known in advance and a railway control center controls the movement of each train. Furthermore, from the point of view of the public grid, a fleet of moving train can be considered to be a source of stored energy fed by the kinetic energy of the moving trains.

In three-phase power systems, power flow routing has been traditionally performed by phase-shifting transformers, which are a special type of transformer allowing to vary the phase shifting between the primary and the secondary side normally in a controlled way [8]. Since the late 1990s, the development of FACTS devices has allowed different kind of power flow controls in AC transmission grids [9], normally relying on the notion of series/parallel compensation. More recently, similar concepts were developed for distribution networks, especially as the smart grid paradigm began to be adopted [10]-[12]. Finally, although direct conversion of the power (as opposed to series/parallel compensation schemes) is still problematic due to the large amount of power to be managed in distribution networks, it may be a feasible approach in the future.

This paper presents an enhancement for those railway power systems (RPS) using segmented topologies. The proposed system allows an increased degree of controllability of the infrastructure which enables, for instance, power routing.

In the field of railway electrification, RPSs are normally classified in two groups according to the characteristics of the voltage used in the power supply: low-frequency systems (which include DC, 16.7 Hz, 20Hz and 25Hz) and industrial-frequency systems (50Hz and 60Hz). Although all these systems can use segmented topologies, it is in industrial-frequency systems where segmentation is commonly used [13].

This paper has five more sections. Section II describes the topology of the AC-fed RPSs with neutral zones (often referred to as industrial-frequency RPS). Section III describes the modification proposed in this paper and how it
modifies the power distribution in a usual railway grid. Section IV proposes an optimization-based methodology to decide the dimensioning of the new elements to be installed. Its purpose is to evaluate the improvements that can be achieved with this technology, and therefore, its pertinence. This optimization methodology is then applied in Section V using a case study based on a 550-km section of the Madrid-Barcelona high-speed line and the results are analyzed. Finally, Section VI outlines the conclusions of this work.

II. POWER SUPPLY SYSTEMS USED IN RAILWAYS

Industrial-frequency RPSs are normally split into several feeding sections (FS), each of which is fed from the three-phase public transmission or distribution grid (PTDG) through a single transformer located in a traction substation (TSS). Neutral zones (NZ) are used to ensure electrical insulation between adjacent FSs.

Depending on the railways requirements, the FSs can be fed with the single-phase system with a neutral (referred to as 1x) or the unbalanced two-phase autotransformer (AT) system with a neutral (referred to as 2x), as illustrated in Figs. 1 and 2, respectively.

![Fig. 1. Structure of a 1x RPS](image1)

In the 2x system, even though a two-phase system is set up, the loads are connected to only one phase (referred to as positive phase) and the neutral. The ATs are used to allow the flow of power from the other phase (referred to as the negative phase), which is unloaded [14].

![Fig. 2. Structure of a 2x RPS](image2)

In both Fig. 1 and Fig. 2, the symbols $U_{R_S}$, $U_{S_T}$, and $U_{T_R}$ refer to the voltages in the PTDG used to feed each transformer. Normally, the phases are rotated to reduce the unbalances caused by the railway grid in the PTDG.

III. PROPOSED ENHANCEMENT TO POWER SUPPLY SYSTEMS

A. Description of the modified system

The proposed modification consists in the addition of a power-transferring device (PTD) connected in parallel to both sides of each NZ (see Fig. 3). A PTD has to be able to transfer, from one FS to the other, the active and reactive power specified by a control system, referred to as Energy Management System (EMS), for the positive phase as well as for the negative phase (in AT-based systems). In Fig. 3, symbols $S_{pos,i}$ and $S_{neg,i}$ refer to the apparent power transferred by the positive and negative phases respectively at the side $i$, with $i \in \{1,2\}$.

It should be noted that, although the rated voltages are the same in all the FSs, there are phase shifts between adjacent FSs due to the phase selection when connecting the transformers to the PTDG. Also, in 2x systems a phase shift exists between positive and negative voltages.

Fig. 4 shows the architecture of the enhanced 1x RPS in which, for the sake of clarity, two EMS have been considered. Fig. 5 shows the architecture of the enhanced AC 2x RPS with, for sake of clarity, also two EMS. The acronym TSS-PTD refers to the PTDs located in the NZ of the TSS. The acronym NZ-PTD refers to the PTDs located in the other NZs.

![Fig. 3. Description of the power transferring devices (PTDs)](image3)

Although the EMS architecture details are beyond the scope of this paper, NZ are normally operated by a substation (TSS or NZ-specific substation, depending on the cases), where reliable communication channels are available, allowing a centralized as well as a distributed-control system for the modified system. While the centralized architecture enables the control system to perform a global optimization of the operation, especially in terms of energy-management efficiency, the distributed control yields enhanced redundancy for the railway systems.
B. Description of operation of the modified system

The power-balance expressions can be established for the general case (PTDs with star topology, with a higher number of terminals):

\[
\sum_{s=1}^{N_s} \sum_{p \in \{pos, neg\}} s_{p,s} = 0
\]

where \( N_s \) is the number of sides of the PTDs.

For the two-side PTDs represented in Fig. 3, \( N_s = 2 \) and Eq. (1) becomes:

\[
S_{pos,1} - S_{pos,2} + S_{neg,1} - S_{neg,2} = 0
\]

The power balance can also be expressed as a function of voltages and currents at the terminals of the PTDs using the following expression:

\[
\sum_{s=1}^{N_s} \sum_{p \in \{pos, neg\}} (V_{p,s} \cdot \delta \theta_{p,s}) \cdot (I_{p,s} \cdot \delta \varphi_{p,s})^* = 0
\]

where \( V_{p,s} \) and \( I_{p,s} \) are the voltage and the input current modules respectively in the terminal \( (p, s) \) (side \( s \) and phase \( p \) of the PTD), \( \theta_{p,s} \) is the angle of the voltage in the terminal \( (p, s) \), \( \varphi_{p,s} \) is the angle between the voltage and the current in the terminal \( (p, s) \), symbol \( * \) represents the conjugate operand.

If the angle \( \theta_{p,s} \) is taken as the reference in each terminal, (3) can be expressed as follows:

\[
\sum_{s=1}^{N_s} \sum_{p \in \{pos, neg\}} (V_{p,s} \cdot \delta \theta_{p,s}) \cdot (I_{p,s} \cdot \delta \varphi_{p,s})^* = 0
\]

Finally, if each phase is managed separately avoiding any power transfer between different phases, (4) becomes:

\[
\sum_{s=1}^{N_s} (V_{p,s} \cdot \delta \varphi_{p,s}) \cdot (I_{p,s} \cdot \delta \varphi_{p,s})^* = 0 \quad \text{for each phase } p
\]

If the voltages on both sides of a PTD are assumed to have the same amplitude, (5) reduces to the following expression:

\[
\sum_{s=1}^{N_s} I_{p,s} = 0 \quad \text{for each phase } p
\]

where \( I_{p,s} = I_{p,s} \cdot \delta \varphi_{p,s} \).

Fig. 6 illustrates the way the currents in each of the phases are modified by adding the PTDs to the infrastructure.

Fig. 7 shows how the NZ-PTD modifies the current steps in the catenary, increasing them in one side and decreasing them in the other. For a given phase, in the \( k \)th PTD, the injected currents at each time instant \( t \) have to be \( I_{PTD,k,t} \) on one side and \(-I_{PTD,k,t}\) on the other side.

Because the current supplied to the trains do not change if PTDs are added, the following expression can be established:

\[
I_{sup,k,t} = I_{w/o} + I_{PTD,k,t} - I_{PTD,k-1,t}
\]

where \( I_{w/o} \) is the current supplied by the transformer of sector \( k \) in the original system (without PTDs), \( I_{sup,k,t} \) is the current supplied by the transformer in the sector \( k \) in the enhanced system (with PTDs) and \( I_{PTD,k,t} \) is the current transferred by the PTD k.

The power \( S_{sup,k+1,t} \) supplied by the substation containing transformers \( k \) and \( k+1 \) (see Fig. 8) can be derived from (7):

\[
S_{sup,k+1,t} = V_{sup} \cdot (I_{sup,k,t} + I_{sup,k+1,t})^*
\]

where \( V_{sup} \) is the supply voltage referred to the low voltage side of the transformer.

If \( I_{sup,k,t} \) and \( I_{sup,k+1,t} \) are expressed as a function of the currents through the PTDs, the expression (8) becomes:

\[
S_{sup,k+1,t} = V_{sup} \cdot (I_{w/o} + I_{sup,k+1,t} + I_{PTD,k+1,t} - I_{PTD,k-1,t})^*
\]

Two important remarks can be formulated based on (9). The power \( S_{sup,k+1,t} \) supplied by the substation to the sectors \( k \) and \( k+1 \) does not depend on \( I_{PTD,k,t} \) (the current transferred by the TSS-PTD of the substation). And consequently, the real function of the TSS-PTDs has to be load balancing between the two transformers of the same substation.

IV. OPTIMAL RATING AND OPERATION

In order to evaluate the advantages of the system, an operation strategy of the infrastructure has been considered consisting in minimizing the total cost of the electricity supply. In this section, an optimization model is proposed to determine the most efficient operation of the PTDs and the optimal investments in PTDs to be done. This model takes into account: (i) the train power consumptions that have been previously obtained with a rail traffic simulator [15].
and (ii) the electrification to be upgraded (electrical description of the substations and catenaries) [16].

As indicated in (10), the cost of electricity $C_{\text{elec}}$ is dependent on the usage of energy and the capacity of power allocated to a customer; that is,

$$C_{\text{elec}} = C_{\text{ene}} \cdot E + C_{\text{pc}} \cdot P_{\text{max}}$$

where $C_{\text{ene}}$ is the cost of the energy in [€/kWh], $E$ is the total energy consumption [kWh], $C_{\text{pc}}$ is the cost of the allotted power capacity in [€/kW] and $P_{\text{max}}$ is the allotted power capacity. Depending on the case, $C_{\text{elec}}$ and $C_{\text{pc}}$ may depend on the specific hour of the day.

The optimization determines the value of the variables listed in Table 1 in order to minimize the economic impact of installing and operating PTDs, which include both the required investments but also the savings in the electricity bill due to the proposed enhancement.

<table>
<thead>
<tr>
<th>INV</th>
<th>Required investments [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>Operating manageable cost [€], as defined in (14)</td>
</tr>
<tr>
<td>$I_{\text{rated},k}$</td>
<td>Rated current of the PTD $k$ [A]</td>
</tr>
<tr>
<td>$I_{\text{PTD},k,t}$</td>
<td>Current through PTD $k$ at the instant $t$ [A]</td>
</tr>
<tr>
<td>$C_{\text{loss}}$</td>
<td>Cost of the energy losses in the catenary [€]</td>
</tr>
<tr>
<td>$C_{\text{lossx}}$</td>
<td>Cost of the energy losses in the transformers [€]</td>
</tr>
<tr>
<td>$C_{\text{pow}}$</td>
<td>Cost of the power capacity [€]</td>
</tr>
</tbody>
</table>

The objective function to be minimized is as follows:

$$\text{INV} + \text{OC}$$

(11)

The investments include the cost of installing the PTDs in an existing infrastructure. Because voltages levels are known, the cost of each of the PTDs has been assumed to be proportional to the rated current of the PTDs:

$$\text{INV} = C_{\text{dev}} \cdot \sum_{k \in \text{PTD}} I_{\text{rated},k}$$

(12)

where $C_{\text{dev}}$ is the cost per current unit of the PTD [€/A].

The current through the PTDs must be lower than its rated value to avoid a thermal destruction of the device. As the PTDs are bidirectional, the following constraint holds:

$$-I_{\text{rated},k} \leq I_{\text{PTD},k,t} \leq I_{\text{rated},k}$$

for each $t$ (13)

The operating manageable costs include the costs of the losses incurred in the transformers and the catenary as well as the cost of the allotted power capacity:

$$\text{OC} = C_{\text{loss}} + C_{\text{lossx}} + C_{\text{pow}}$$

(14)

where $C_{\text{ene}} \cdot E = C_{\text{loss}} + C_{\text{lossx}}$ and $C_{\text{pc}} \cdot P_{\text{max}} = C_{\text{pow}}$.

The cost of the losses in the transformer is as follows:

$$C_{\text{loss}} = C_{\text{ene}} \cdot \sum_{k \in \text{PTD}} \left( I_{\text{sup},k,t}^{\text{w/o}} + I_{\text{PTD},k+1,t} - I_{\text{PTD},k-1,t} \right)^2$$

(15)

where $\delta_k$ is the time step used in the traffic simulations and the non-bold symbols $I_k^x$ refer to the modules of the phasors $I_k^x$ for every index $x$ and $y$ (a power factor equal to one has been assumed).

The cost of the losses in the catenary is expressed by the following expression:

$$C_{\text{lossx}} = C_{\text{ene}} \cdot \sum_{k \in \text{PTD}} \left( \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} R'_{k} D_{j,k,t} (I_{j,t} - 1) \right)^2$$

(16)

where $CCS_{s,t}$ is the set of all the CCSs within the $s^{th}$ FS (see Fig. 7) at time step $t$, $I_{j,t}$ is the current in the $j^{th}$ CCS of a specific set $CCS_{s,t}$ at time step $t$. $D_{j,k,t}$ is the length of the $j^{th}$ CCS at time step $t$ and $R'_{k}$ is the resistance per length unit in the $k^{th}$ FS.

Equation (16) can be rewritten as follows:

$$C_{\text{lossx}} = C_{\text{ene}} \sum_{k \in \text{PTD}} \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} R'_{k} D_{j,k,t} (I_{j,t} - 1)$$

(17)

where

$$\left\{ \begin{array}{l} A_{k,t} = \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} D_{j,k,t} I_{j,t} \\ B_{k,t} = 2 \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} D_{j,k,t} I_{j,t} \\ C_k = L_k \end{array} \right.$$  

and $L_k$ is the length of sector $k$.

As the restrictions (17) and (15) are quadratic with the set of variables $I_{\text{PTD},k,t}$, only non-linear solvers can be used to solve the optimization problem. Hence, the problem is transformed into a mixed integer programing (MIP) problem by performing a piecewise linearization of the losses in which the auxiliary variables described in Table 2 are considered. To make the branch-and-bound process more efficient, SOS2 (Special Ordered Sets type 2) have been used [17], [18].

| $I_{\text{PTD,SOS},k,t}$ | Variable taking non-zero values only in the two adjacent values of $s$ whose PTD currents are closer to $I_{\text{PTD},k,t}$ (see Fig. 9), where is the index of the considered step. |
| $I_{\text{TR,SOS},k,t}$ | Variable taking non-zero values only in the two adjacent values of $s$ whose currents are closer to the total current in transformer $k$ (see Fig. 9). |

The following additional restrictions are required for formulating the problem in terms of the SOS2 variables:

$$\sum_{s} I_{\text{PTD,SOS},k,t} = 1$$

(19)

$$\sum_{s} I_{\text{TR,SOS},k,t} = 1$$

(20)

In the optimization model, instead of using expressions (17) and (15) to calculate the power losses, $LOSSCAT_{k,t,s}$ and $LOSSX_{k,t,s}$ are defined with the pre-calculated values of the losses at the catenary at the transformer in section $k$ at instant $t$ for the current step $s$ (Y-axis in Fig. 9) resulting in:

$$C_{\text{loss}} = C_{\text{ene}} \sum_{k \in \text{PTD}} \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} \cdot LOSSCAT_{k,t,s}$$

(21)

$$C_{\text{lossx}} = C_{\text{ene}} \sum_{k \in \text{PTD}} \sum_{s} I_{\text{sup},k,t}^{\text{w/o}} \cdot LOSSX_{k,t,s}$$

(22)

Finally, the cost of the power capacity is:

$$C_{\text{pow}} = C_{\text{pc}} \cdot \sum_{k \in \text{PTD}} \max_x \left( I_{\text{sup},k,t}^{\text{w/o}} + I_{\text{PTD},k+1,t} - I_{\text{PTD},k-1,t} \right)$$

(23)
where $C_{pc_j}$ is the cost of the allotted power capacity in [€/A], assuming a given voltage in the power measuring point.

V. CASE STUDY

To evaluate the usefulness of the proposed system, a 549 km section of the high-speed line (HSL) between Madrid and Barcelona is considered (from km 0 to km 549.153). In the study, the costs of the electrical power supply of the original and the optimized systems are compared.

Description of the case Fig. 10 shows the simplified outline of the Madrid-Barcelona high-speed line. Except for the first 15 km, where the maximum speed is 250 km/h, trains can drive at 300 km/h for the rest of the studied section. There is an additional restriction in speed when arriving at Zaragoza (80 km/h at km 307) if the bypass is not taken.

![Simplified outline of the Madrid-Barcelona high speed line](image)

Fig. 10. Simplified outline of the high-speed line between Madrid-Barcelona

Table 3 shows the sectors in this line section, the substation feeding them, their location and the system (single-phase or two-phase). The location of the substations would also correspond to the location of the TSS-PTDs.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Substation</th>
<th>Location [km]</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Villaverde (1x60MVA)</td>
<td>0(*)</td>
<td>1-ph</td>
</tr>
<tr>
<td>2, 3</td>
<td>Anchuelo (2x60MVA)</td>
<td>44.332</td>
<td>2-ph</td>
</tr>
<tr>
<td>4, 5</td>
<td>Brihuega-El Espino (2x60MVA)</td>
<td>86.550</td>
<td>2-ph</td>
</tr>
<tr>
<td>6, 7</td>
<td>Medinaceli-Las Lastras (2x60MVA)</td>
<td>152.417</td>
<td>2-ph</td>
</tr>
<tr>
<td>8, 9</td>
<td>Terrer-Vega (2x60MVA)</td>
<td>214.819</td>
<td>2-ph</td>
</tr>
<tr>
<td>10, 11</td>
<td>Rueda de Jalón (2x60MVA)</td>
<td>268.884</td>
<td>2-ph</td>
</tr>
<tr>
<td>12, 13</td>
<td>Zaragoza-Alfidén (2x60MVA)</td>
<td>316.434</td>
<td>2-ph</td>
</tr>
<tr>
<td>14, 15</td>
<td>Peñalba (2x60MVA)</td>
<td>377.587</td>
<td>2-ph</td>
</tr>
<tr>
<td>15, 17</td>
<td>Montagut (2x60MVA)</td>
<td>430.466</td>
<td>2-ph</td>
</tr>
<tr>
<td>18, 19</td>
<td>L’Espluga (2x60MVA)</td>
<td>490.795</td>
<td>2-ph</td>
</tr>
<tr>
<td>20</td>
<td>La Gornal (1x60MVA)</td>
<td>549.253</td>
<td>2-ph</td>
</tr>
</tbody>
</table>

(*) The location has been modified from its actual location, in order to match with the topology expected by the optimization model.

Table 4 shows the location of the neutral zones of the line, which would also correspond to the location of NZ-PTDs.

<table>
<thead>
<tr>
<th>Side sectors</th>
<th>Location [km]</th>
<th>Side sectors</th>
<th>Location [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>20.999</td>
<td>11, 12</td>
<td>284.001</td>
</tr>
<tr>
<td>3, 4</td>
<td>67.693</td>
<td>13, 14</td>
<td>346.707</td>
</tr>
<tr>
<td>5, 6</td>
<td>112.174</td>
<td>15, 16</td>
<td>408.301</td>
</tr>
<tr>
<td>7, 8</td>
<td>188.963</td>
<td>17, 18</td>
<td>457.675</td>
</tr>
<tr>
<td>9, 10</td>
<td>241.250</td>
<td>19, 20</td>
<td>518.628</td>
</tr>
</tbody>
</table>

Siemens S-103 trains have been considered, with trains traveling every 10 min in each direction. Fig. 11 summarizes the characteristics of these trains.

Based on the aforementioned data, the power consumption of the trains in both directions has been obtained. Fig. 12 and Fig. 13 show the power consumption and the speed of the trains in the Madrid-Barcelona and Barcelona-Madrid journeys respectively, sampled every 5 s. A power factor of 1 has been assumed.
To simplify the evaluation of the performance of the system, the periodic traffic mesh with trains every 10 min has been considered to operate 9 hours per day, 365 days a year. The number of operating hours may seem a bit low, but the frequency corresponds to a peak period.

For this average operating conditions, Table 6 shows the estimated costs of the electricity which has been considered:

**Table 6. Cost of the electricity (averaged for >145kV, 2012, Spain)**

<table>
<thead>
<tr>
<th>Power capacity (€/kW/year)</th>
<th>23.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (€/kWh)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

### A. Evaluation of the enhanced system

In order to assess the advantages of the proposed system, its ability to control the power consumption of every substation and to reach an optimal operation is evaluated. However, the improvements are bounded by the rated currents of the PTDs, which depend on the investments: higher capacity PTDs may produce a more efficient operation, but are certainly more expensive items. As the proposed system is essentially a proof-of-concept, the prices of the PTDs are very difficult to estimate, especially in the long term. For that reason, two scenarios have been studied:

- **Scenario A:** No cost has been considered for PTDs, $C_{dev,1}=0\,€/A$, which leads to an optimal solution that only optimizes the operation, determining the rated currents of the PTDs that minimize the electricity costs. This case provides a good understanding of the best cost reduction the system could reach if this technology would become massively adopted.

- **Scenario B:** The cost of PTDs has been assumed to be 410 €/kVA. Also 10% of this cost will be considered each year to be balanced with the electricity bill reductions, which makes $C_{dev,2}=1025\,€/A$ (at 25kV). In this case, the optimization will find a trade-off between investments and energy savings, which gives a reference of the benefits of the proposed system for reducing the electricity costs.

Fig. 14 and Fig. 15 compare the power supplied by every substation in scenario A and scenario B with the actual electrification, which is used as the reference. With the only exception of the substations “Montagut” and “L’Espluga” in the scenario A, the maximum power peaks are significantly reduced. With the proposed system, all the power supply of the substation “La Gornal” is even effectively assumed by the other substations.

In addition, Table 7 compares the rated values of the PTDs in both scenarios. In the scenario A, as the cost of the PTDs is not considered in the objective function, the rated current of TSS-PTDs take a non-zero value in order to minimize losses in the transformers (as discussed previously, the function of the TSS-PTDs is mainly to balance the load supplied by the two transformer of the substation). In the scenario B, the cost of the PTDs is largely higher compared to the cost of the transformer losses than can be saved by load balancing. Therefore, the optimization leads to not install TSS-PTDs at all.

Table 8 summarizes the enhancements due to adopting the proposed system in the analyzed line. The results obtained for the reference case shows that 94% of the
Table 7. Rated currents of the PTDs.

<table>
<thead>
<tr>
<th>Id</th>
<th>Between sectors</th>
<th>Type</th>
<th>Scenario A Rated I [A]</th>
<th>Scenario B Rated I [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2</td>
<td>NZ-PTD</td>
<td>13837</td>
<td>2444</td>
</tr>
<tr>
<td>2</td>
<td>2,3</td>
<td>TSS-PTD</td>
<td>15181</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>3,4</td>
<td>NZ-PTD</td>
<td>10535</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>4,5</td>
<td>TSS-PTD</td>
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Fig. 14. Current supplied by TSS for each instant. Reference vs Scenario A.

Fig. 15. Current supplied by TSS for each instant. Reference vs Scenario B.

In the scenario A, where PTDs can be rated to obtain the best improvements in the system regardless of their cost, the enhanced system would be able to cut down 32% of the
power capacity costs and very similarly the losses. In this specific case, this would be an upper bound of the enhancement the system could reach.

In the scenario B, where real prices and a charge-off of 10 years have been considered, improvements are lower than in scenario B. However, a reduction of 20% in the manageable costs is reached, mainly due to the savings in the power capacity term (-21%). To achieve this, the system is able to route the electrical power from different substations to the sectors where it is required. In exchange, the currents have to cross longer distances and the electrical losses rise up (+5%). The losses in the transformer are however reduced (-4%).

VI. CONCLUSIONS

This paper has presented a system to improve the AC railway power supply systems which have neutral zones. The system allows an improved degree of controllability of the infrastructure, which allows for instance power routing in traction electrical grids. The proposed system could be an important milestone in the railways smart grids roadmap.

The proposed system would be able to route electrical power routing making possible new ways of operation of railway systems, more reliable and cost-efficient.

As an example of such intelligent operation of the railway power system, a strategy focused on the minimization of the manageable costs of the power supply (including power capacity and losses costs) has been considered in a study case which corresponds to a 550km long section of the high-speed line Madrid-Barcelona. The system would be able to reduce up to 31% these manageable costs.

REFERENCES

Ignacio González Franco received his degree in Industrial Engineering from Vigo University (Spain) and MSc in Railway Engineering from Pontifical University of Comillas (Spain). He has experience in the railways sector, having taken part in different research projects. He is currently writing his doctoral thesis in this optimization of transport infrastructures. He is currently the coordinator of the Energy and Emissions in Railways Research Group and the Technical and Economic Transport Operations Research Group, in the Spanish Railways Foundation (FFE).